2020-01

Why Hydrogen? Myth Busters [video]

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Presentation Start

Why Hydrogen? & lets bust some Myths

Naval Postgraduate School: Discussion on Hydrogen

Jay Keller, Ph.D.
Zero Carbon Energy Solutions

January 21, 2020

Three take away points (1)

- Houston we have a problem!
  - We are running out of conventional energy resources
    - Conventional fuel production will peak about now
    - Non-conventional tar sands and heavy crude only delay the inevitable by maybe 30 to 40 years
    - Recovering product from tar sands releases about 3 times the CO_2 as compared to conventional oil
  - Climate change is real and humans are causing it!
    - Established in May 11, 1910 Glacier National Park had 35 named glaciers, in 2015 there were only 26 named glaciers remaining. (USGS)

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Homework - watch "Chasing Ice" purchase on Amazon for ~$8.00

Three take away points (2)

- Time Scales
  - 50 years the population will double
  - 50 years to change the energy infrastructure
  - 10 years (2030) to mitigate CO_2 emissions to avoid 1.5 ^{o}C global temperature rise above pre-industrial levels (IPCC 6th assessment level), we are already at 0.7 ^{o}C
  - 30 - 50 year life time of large capital investments,
  - 30 - 50 year for market penetration of new technologies
  - 50 years my kids will be in retirement
  - 50 years my grand kids will enjoy a midlife crisis
  - 50 years maybe I will still be alive (I can always hope)
  - 50 years most in this room will be alive!

Three take away points (3)

- Houston we have a solution!
  - Electricity and Hydrogen are needed to transport and store the energy
  - Energy supply in the short term
    - All energy feed stocks need to be used (HC with Carbon Capture and Sequestration (CCS) nuclear, wind, solar, bio-mass …)
  - Longer term (50 years) – plenty of solar energy falls on the earth to power our energy thrust – we need to go after it!

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We have been spoiled with cheap energy – we need to get over it, dig in our heels and solve this!

Topical Outline

- Energy Resources – How much is left? – Not much!
- Climate issues – Do we have a problem? – You Bet!
- What to do about it?
  - Comparison of different technologies
    - Efficiency
    - Fuel switching
    - ..
  - How long will it take?
- Industry Direction
- Energy Carriers

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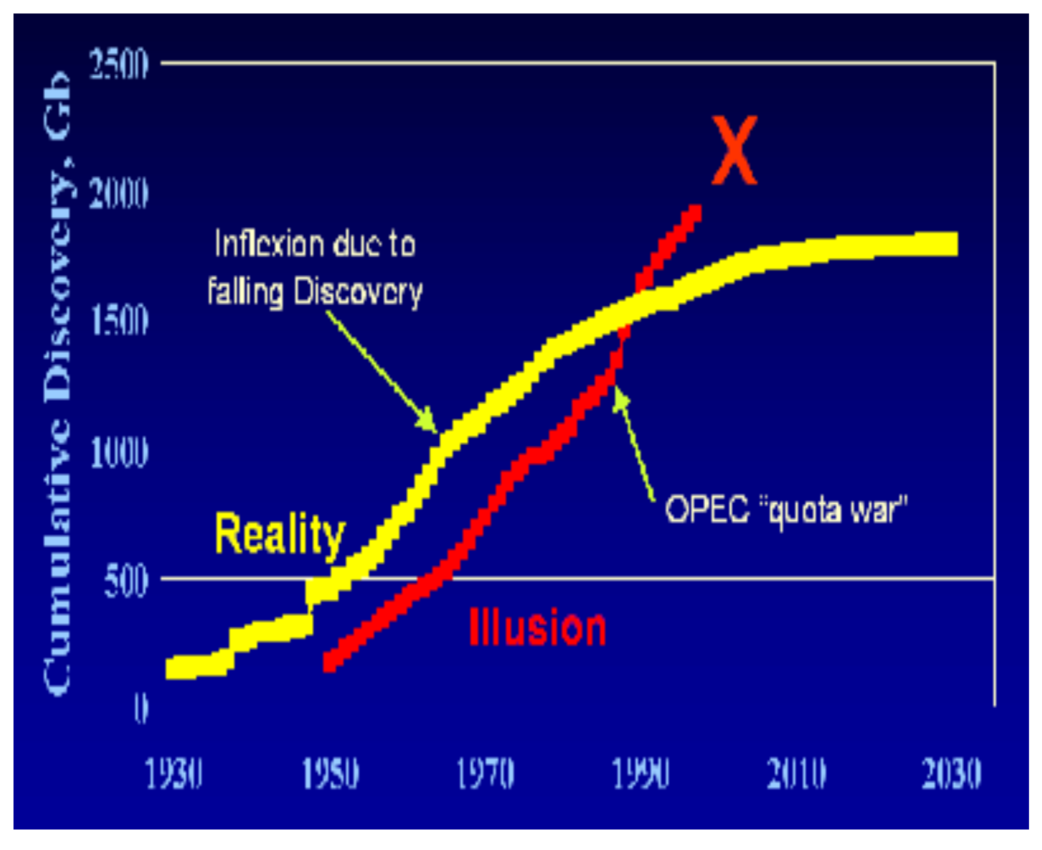
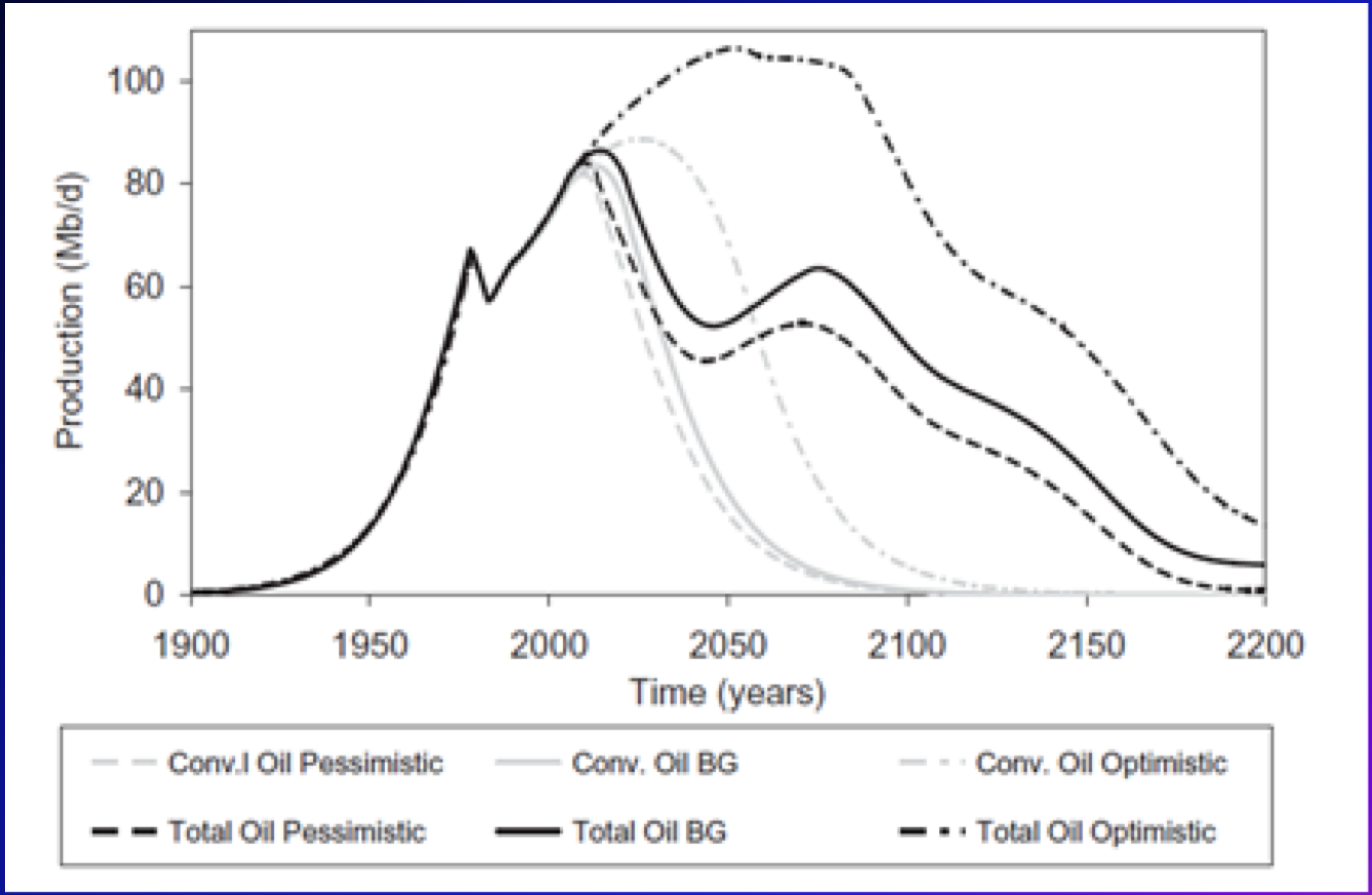
Oil Discovery – getting harder and harder

- Discovery of new conventional oil reserves is reaching an asymptote
- The “big” finds have been found.
- We have been mislead due to imprecise data representation (Illusion Curve)



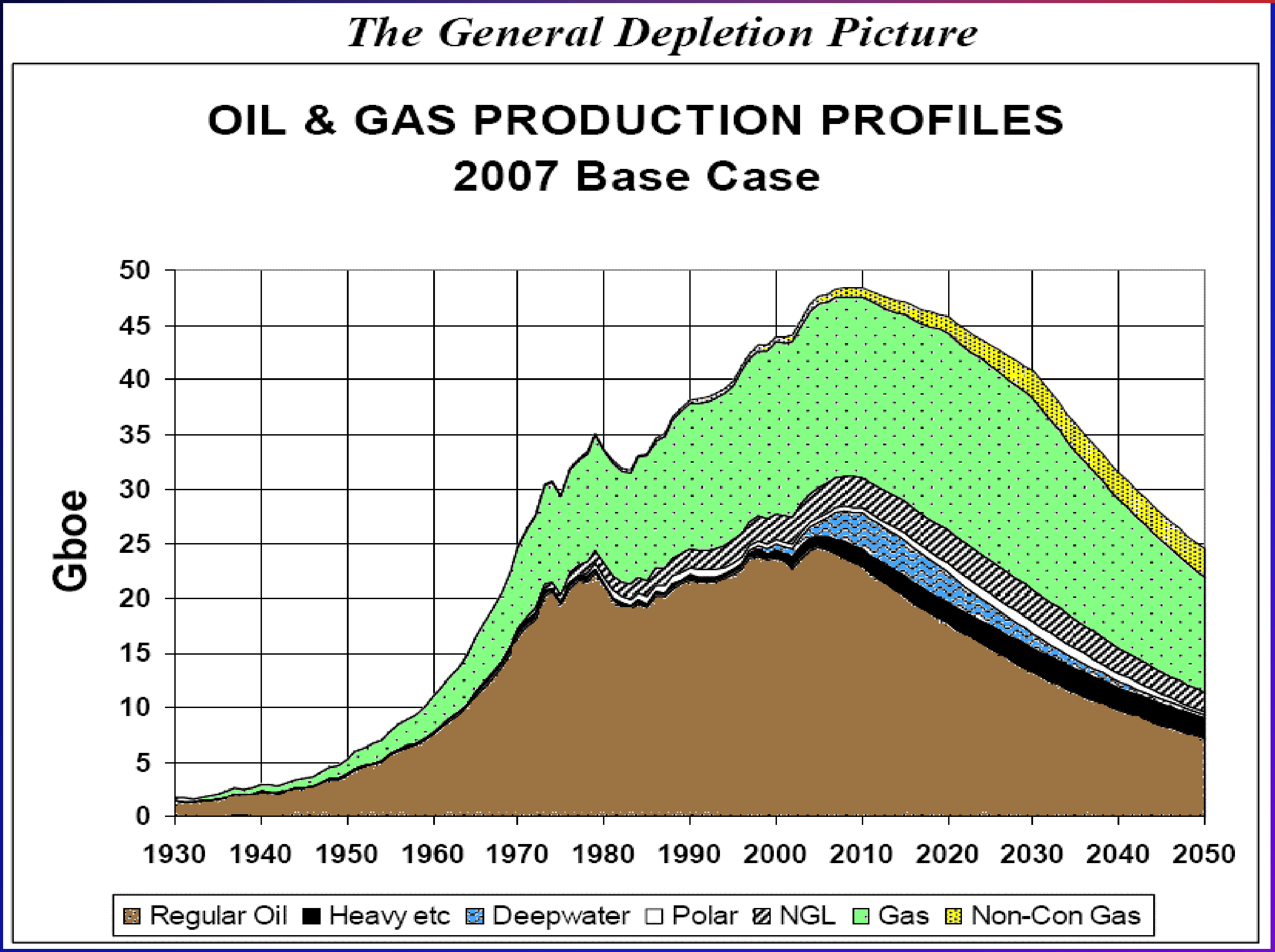
From a presentation given at the Technical University of Clausthal, by C.J. Campell, December 2000
http://www.geogogie.tu-claushtal.de/Campbell/lecture.html

Hubbert's Curve - Total Oil (conventional plus unconventional



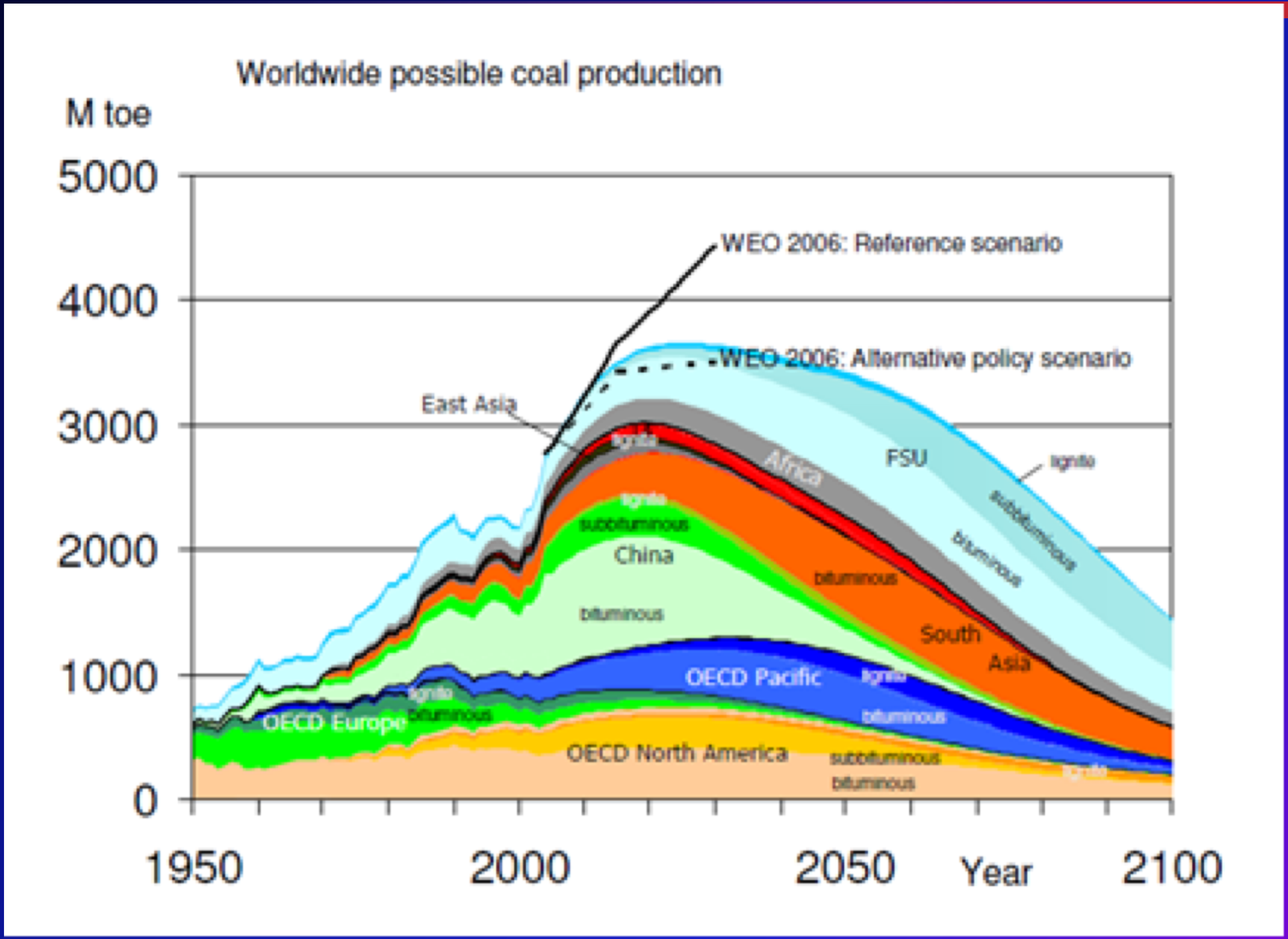
S.H. Mohr and G.M.Evans, Energy Policy **38**, 265 (2010)

Hubbert's Curve – Oil and Gas



http://www.peakoil.net/ ASPO (Association for the Study of Peak Oil)

Hubbert's Curve - Coal Reserves



Zittel W. Schindler J. Coal: Resources and Future Production, Energy Watch Group Paper No. 1/07, available at: http://www.energywatchgroup.org/fileadmin/global/pdf/EWG_Report_Coal_10-07-2007ms.pdf; 2007

Energy and Environmental Sustainability – End Game (2050!)

- IEA estimates population doubling to 11 billion people by 2050
- Assume global per capita energy use of 0.16 Terajoule / yr
  - 2002 G8 Ave & assuming a 25% improvement in energy efficiency
- The global energy demand is then 1.8 x 10^9 Terajoules / yr in 2050
- Where are we going to get this amount of energy and not harm the environment?
  - Not enough Oil, NG, only 20-30 years of U^{238} (unless breeders are used (proliferation problem) and then we need to build 10,000 of the biggest reactors ever built), Clean Coal? (only with CCS), …)
  - Solar (and variants of – wind, bio-mass, …)
    - Incident on earth surface (useful) is about 9.5 x 10^{11} Terajoules / yr @ collection efficiency of 15% means one needs only 1.3% coverage
    - In contrast human settlements and infrastructure ~3%, crops ~11%

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~1.3 % of the land for a reasonable standard of living for all!

We have a serious energy problem – You should be concerned!

- Professor Nathan Lewis from Caltech in 2007 captured this energy challenge very well:
  - "Energy is the single most important technological challenge facing humanity today. Nothing else in science or technology comes close in comparison… with energy, we are in the middle of doing the biggest experiment that humans will have ever done, and we get to do that experiment exactly once. And there is no tomorrow, because in 20 years that experiment will be cast in stone. If we don't get this right, we can say as students of physics and chemistry that we know the world will, on a timescale comparable to modern human history, never be the same."

Powering the Planet (pdf) *by Nathan S. Lewis,* Keynote speech at the first annual California Clean Innovation Conference, held at Caltech on May 11, 2007

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2007 + 20 is 2027 → 7 years from now!

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Why are we working on hydrogen as an energy carrier?

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Eliminate CO_2-eq. Emissions

Why are we working on hydrogen as an energy carrier?

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Eliminate CO_2-eq. Emissions

- From the 4th Assessment (FAR) - for a 2.0-2.4 °C increase in temperature we need to stabilize our CO_2-eq concentrations **to 445-490 ppm by 2050 and beyond** requiring 85-50% reduction in emissions from 2000 levels **(at 2019 we were at 417 PPM)**
- From the 6th Assessment - we need to cap temperature increase to 1.5 °C by 2030 to stop catastrophic climate effects (we are at 0.7 °C in 2019)

*James Hansen et.al. (NASA/Goddard Institute for Space Studies)

Stabilizing Atmospheric CO_2 Concentrations …

- The residence time for CO_2 in the atmosphere is on the order of 120 years *
  - The concentration of CO_2 in the atmosphere is a result of cumulative net emissions **
    - From pre-industrial times to the indefinite future, by every economically developing country, everywhere on the planet . . . <u>and with most emissions yet to come **</u>
- Net Emissions must eventually decline to ZERO <u>whatever the concentration target might be</u>. **

*** Stabilizing Atmospheric Carbon:*
The NCCTI Challenge,
Jae Edmonds, John Clarke
NCCTI Integration Group
Measurement, Monitoring and Validation Workshop, September 26, 2001

* Combustion's Impact on the Global Atmosphere,
M. J. Prather, J.A. Logan
25th symposium (International) on Combustion/The Combustion Institute
1994/pp 1513-1527

We have a serious climate problem – You should be concerned!

- While Nathan S. Lewis feels that energy is the single most important technological challenge facing humanity today, I maintain that:
  - **Climate change is the most profound constraint on energy use facing humanity today.**

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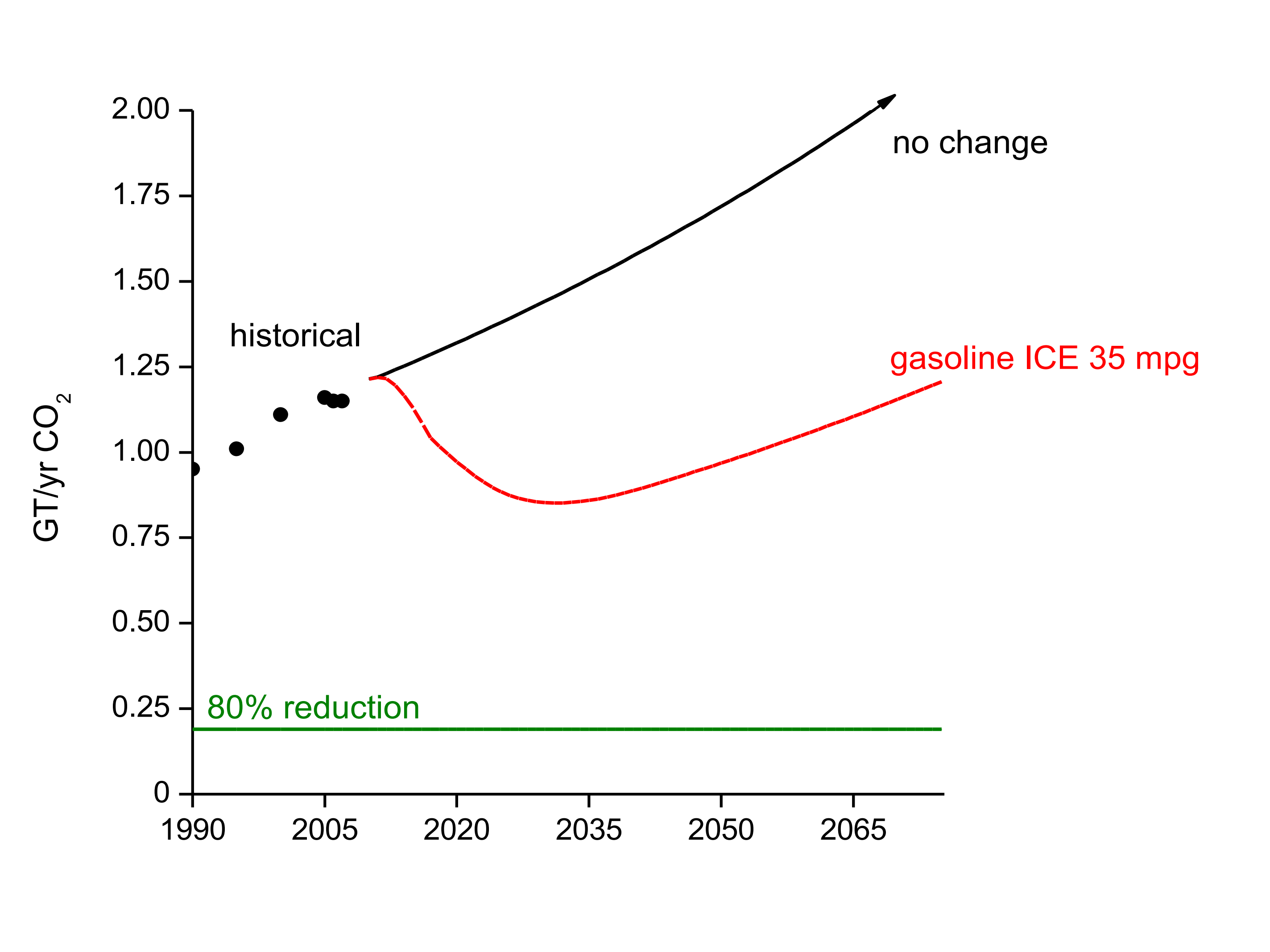
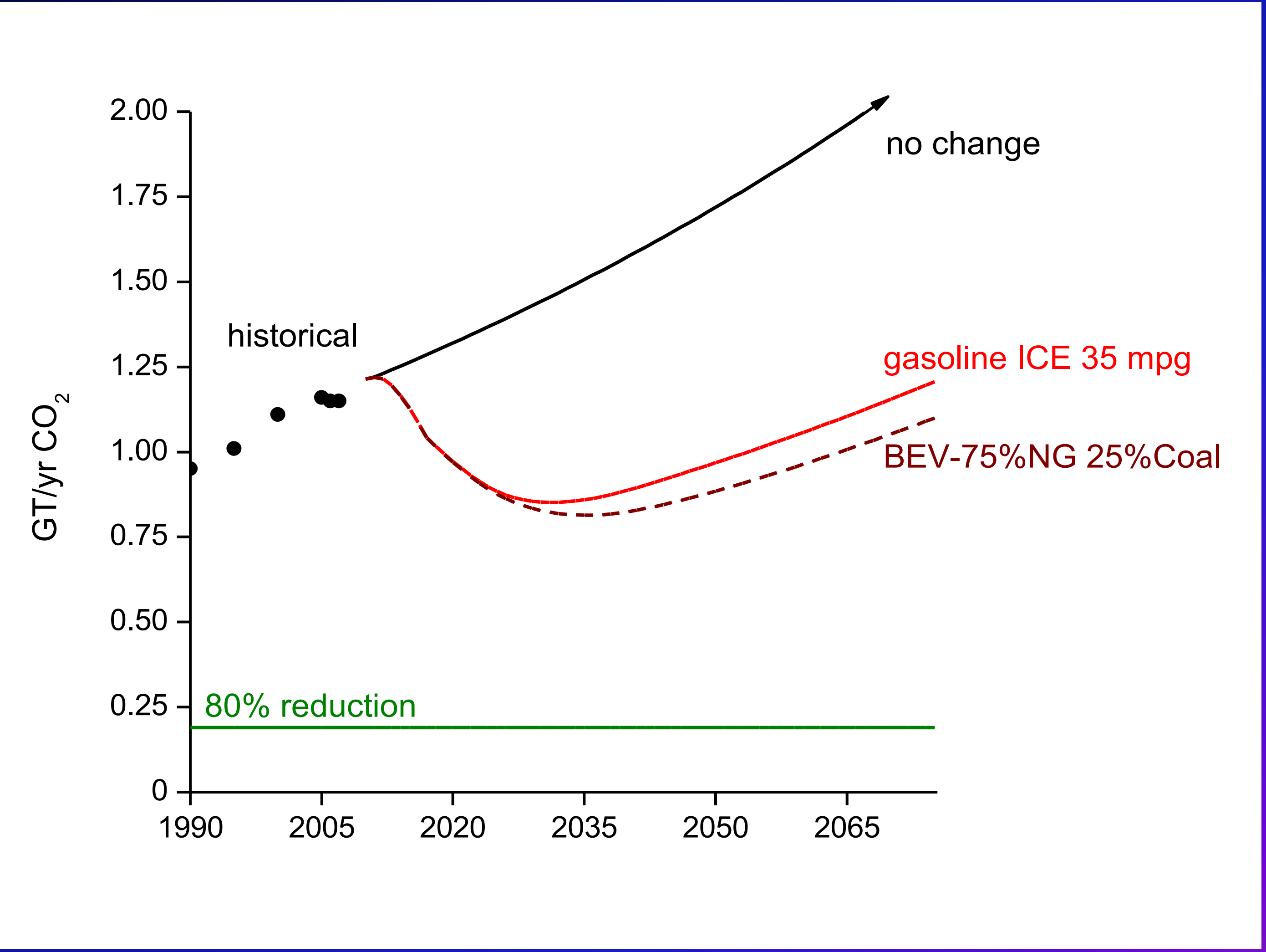
Achieving CAFE standards reduces emissions, but does not meet target



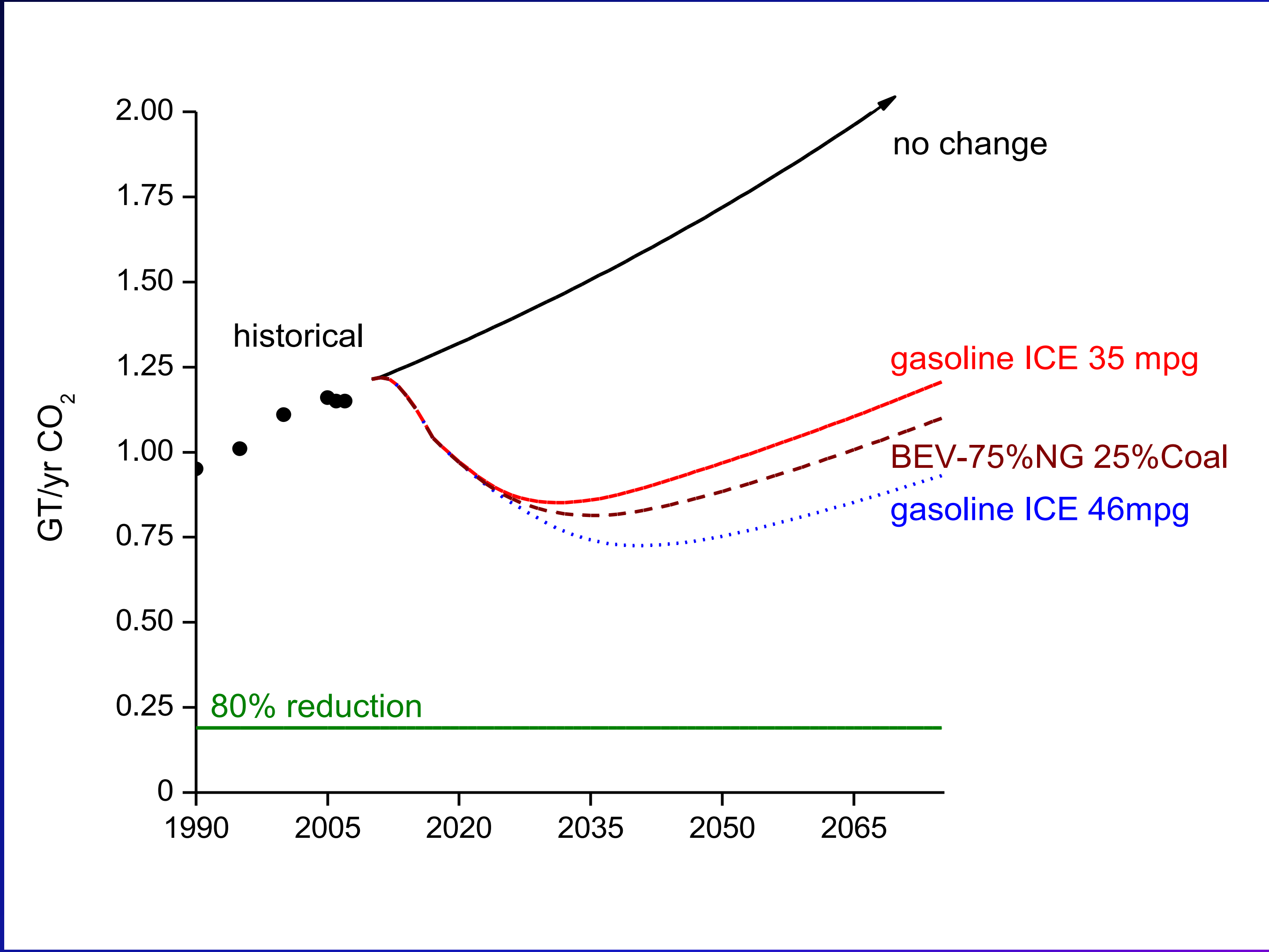
Dave Reichmuth, SNL 2011

Changing to 100% BEV using nighttime marginal power is similar to CAFE



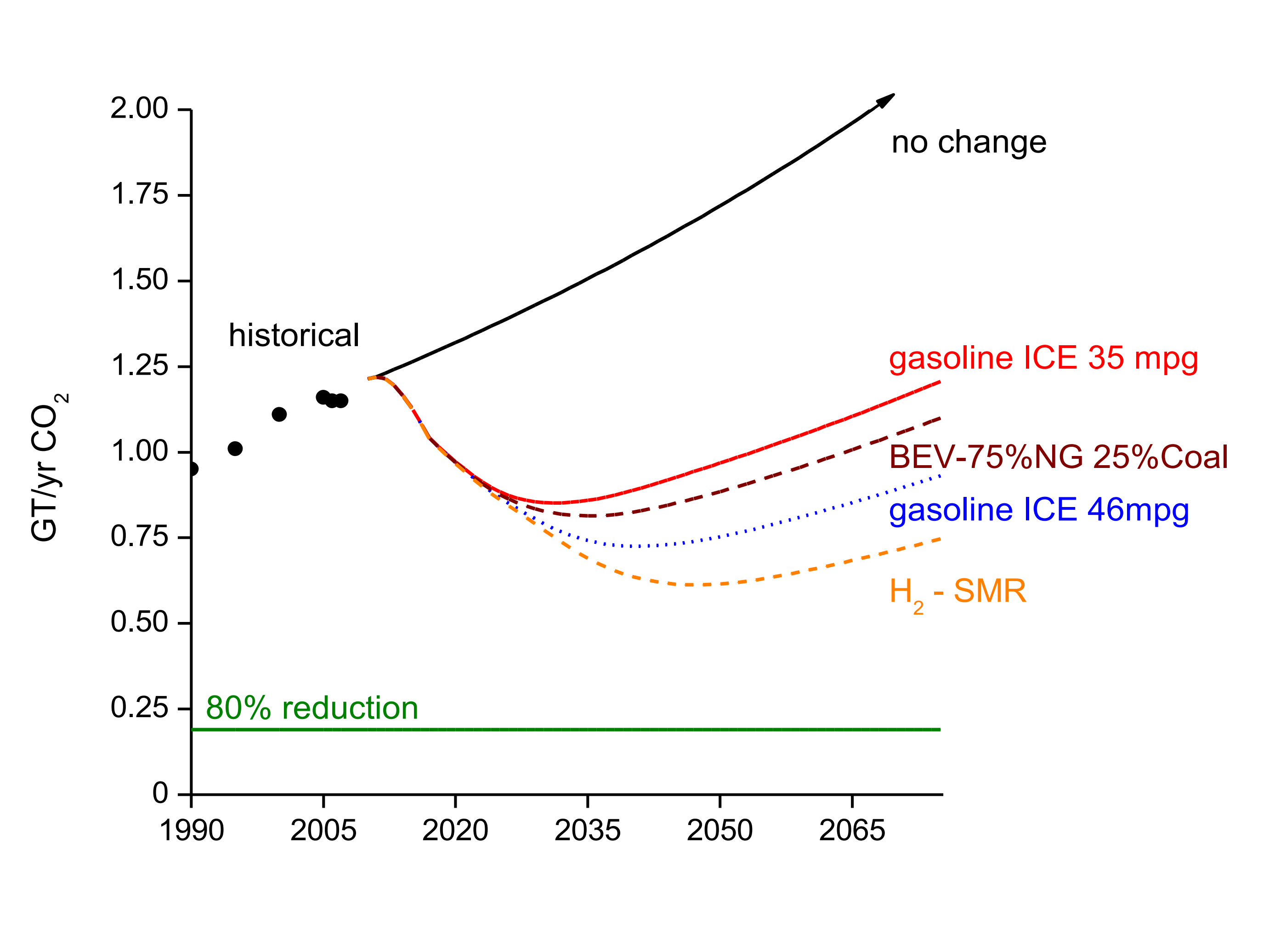
Dave Reichmuth, SNL 2011

Very efficient gasoline ICE vehicles are better than BEVs



Dave Reichmuth, SNL 2011

Using technologies & fuels that exist today, trajectories are similar



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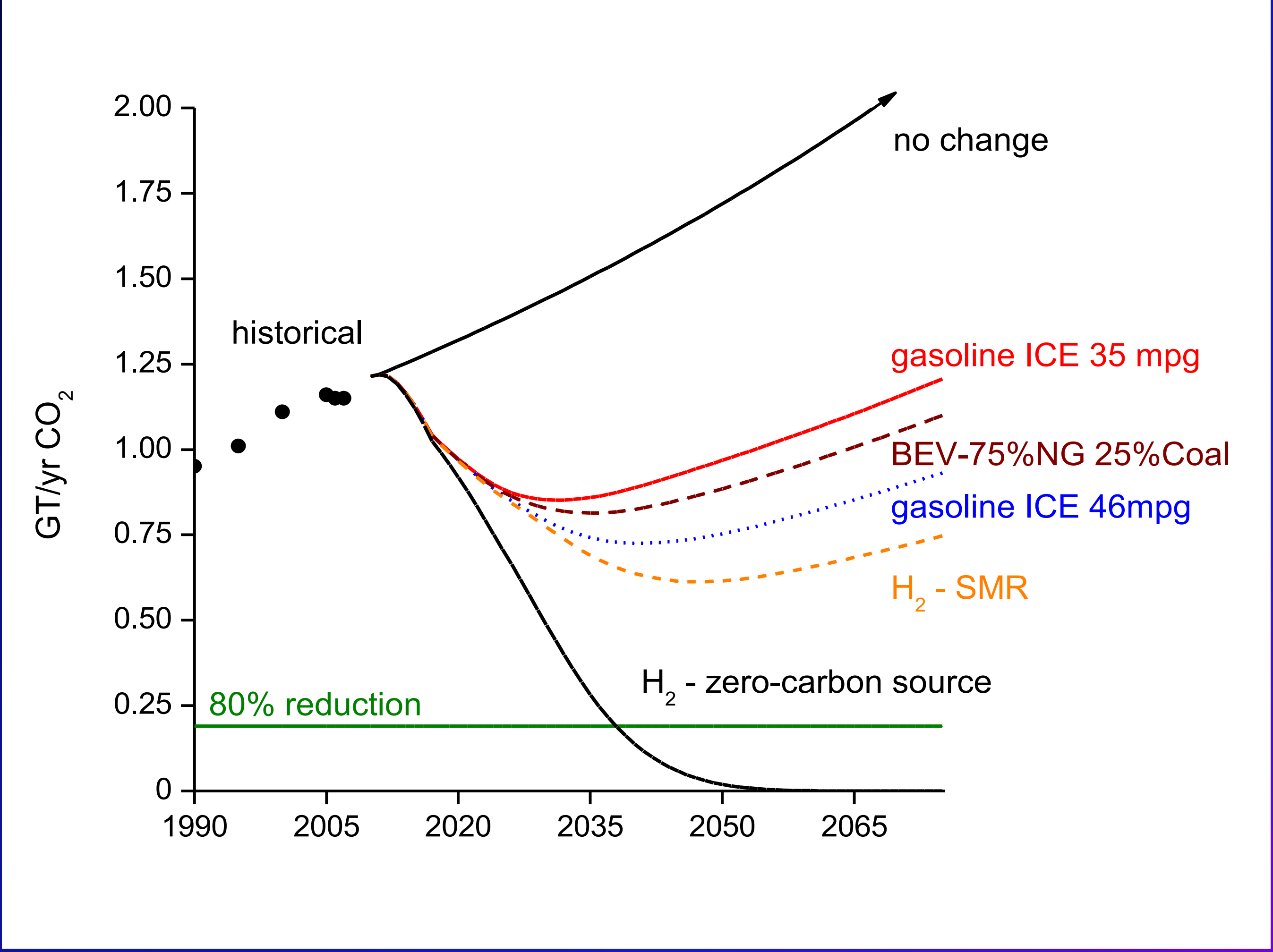
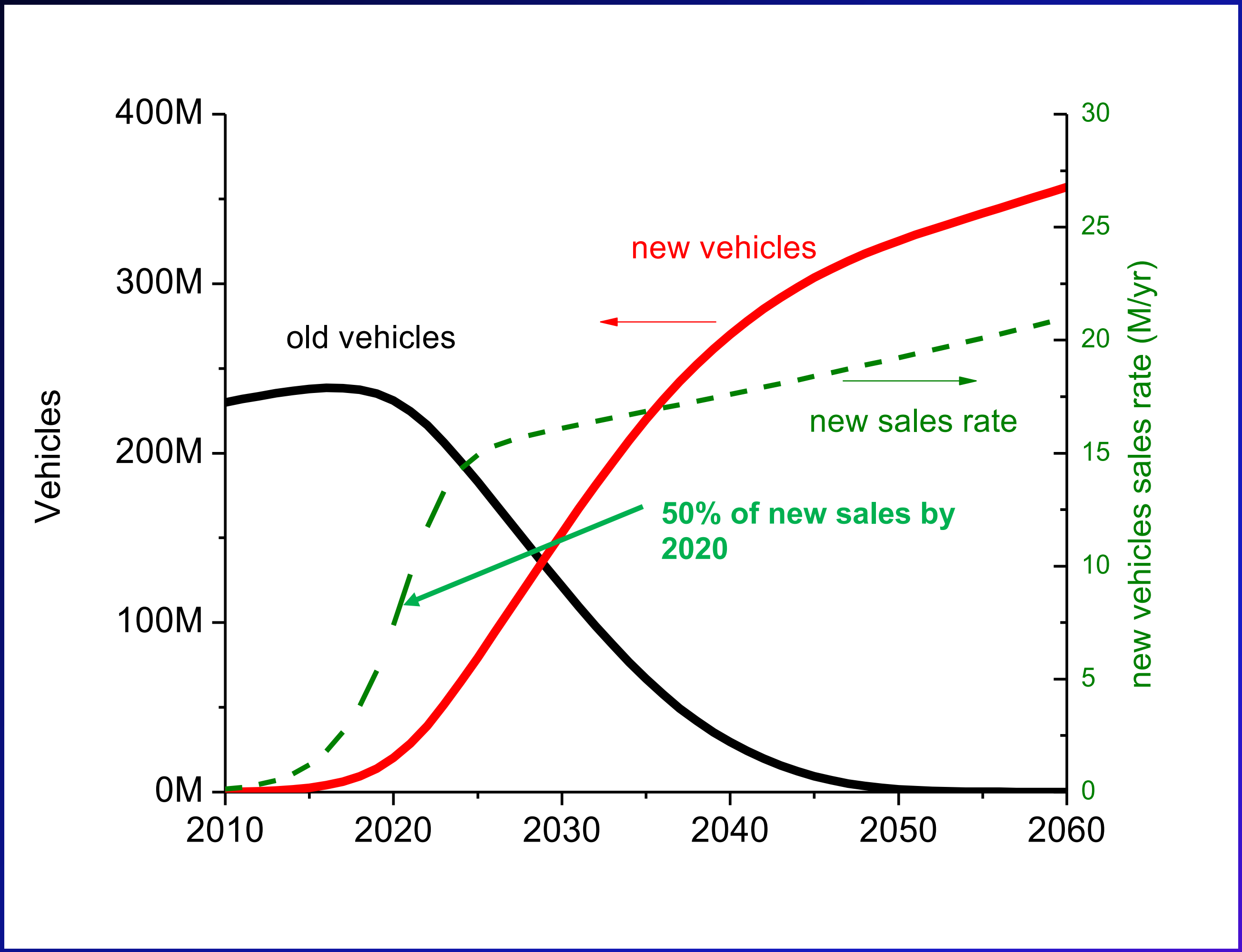
Elimination of carbon from the fuel is required to meet target



Dave Reichmuth, SNL 2011

Vehicle Fleet Roll over Times



Note: the Prius was introduced in the U.S. in 2001. In 2010 (~10 yrs later) the market share from **all** hybrids was only 2.2%

Dave Reichmuth, SNL 2011

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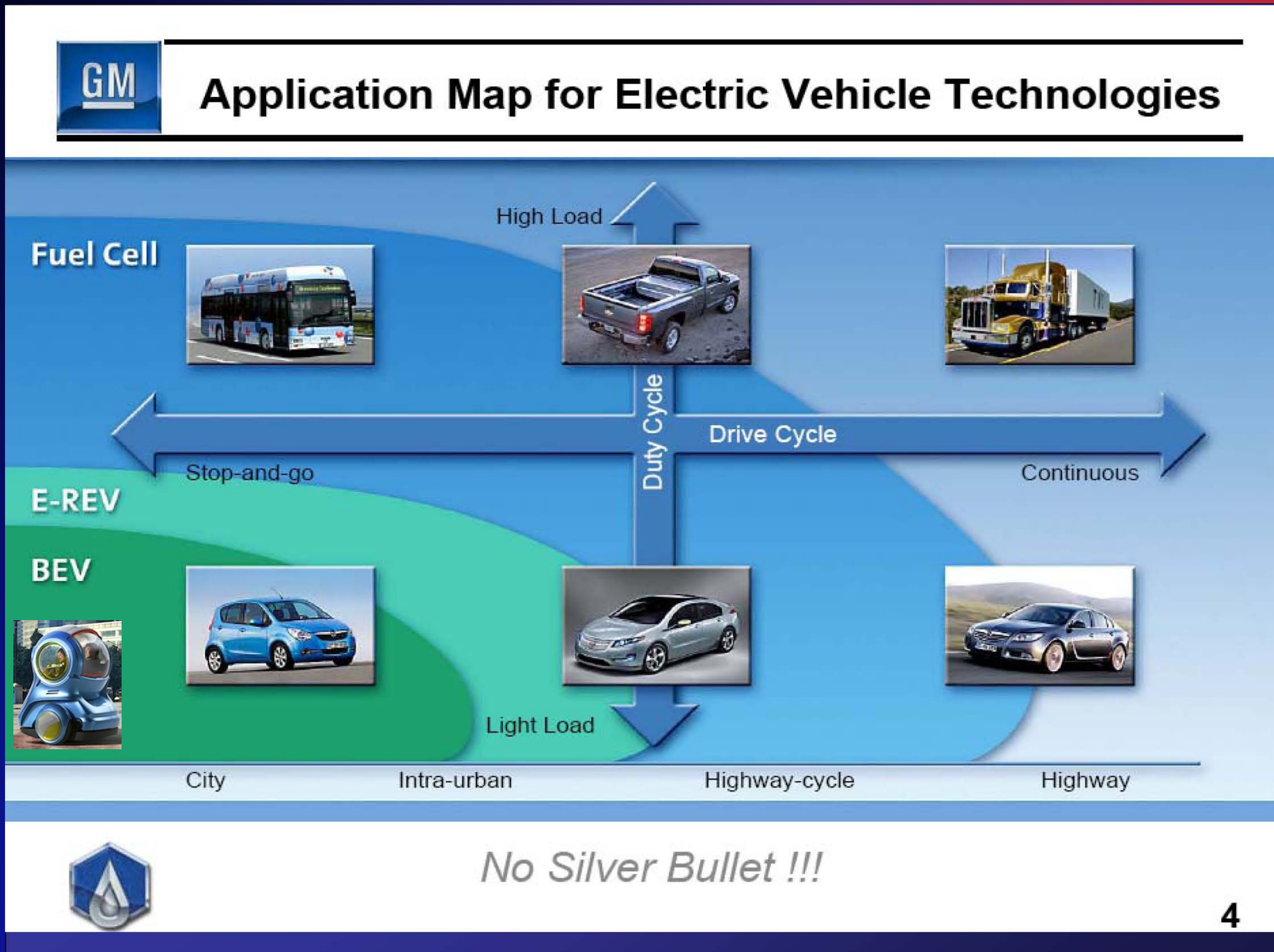
OEM's are Electrifying the fleet



Vehicle manufactures are electrifying the fleet

- Bill Ford said that while his company continues to invest in biofuels, hydrogen and more efficient internal combustion engines, the electrification of the U.S. fleet is inevitable. (Clean Car Advisor - Scott Doggett April 15, 2010).

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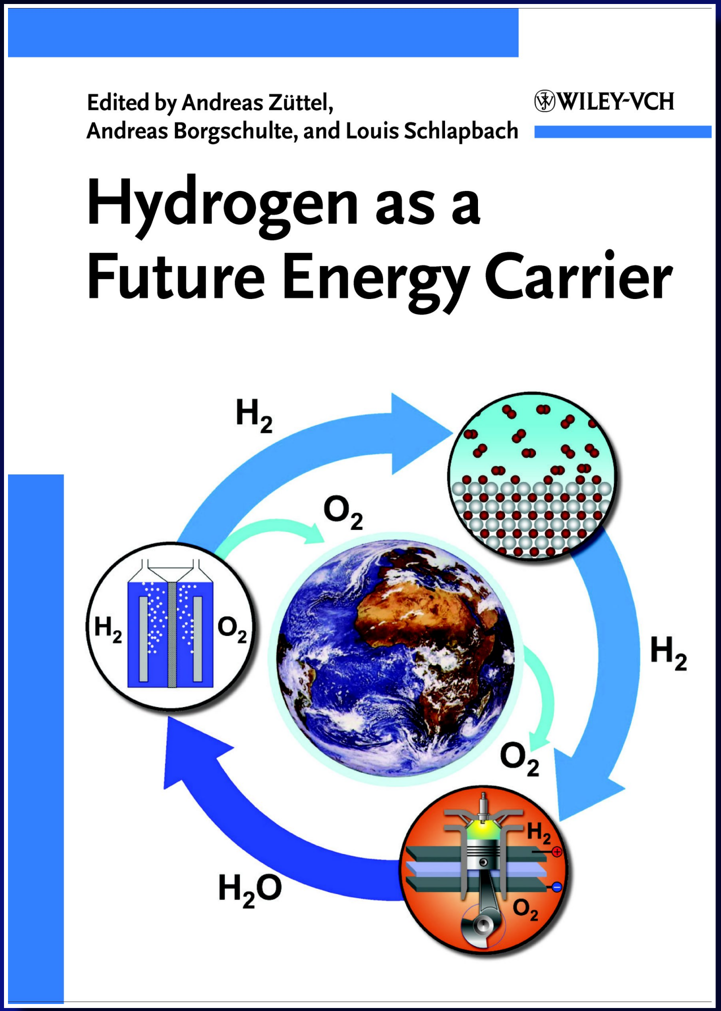
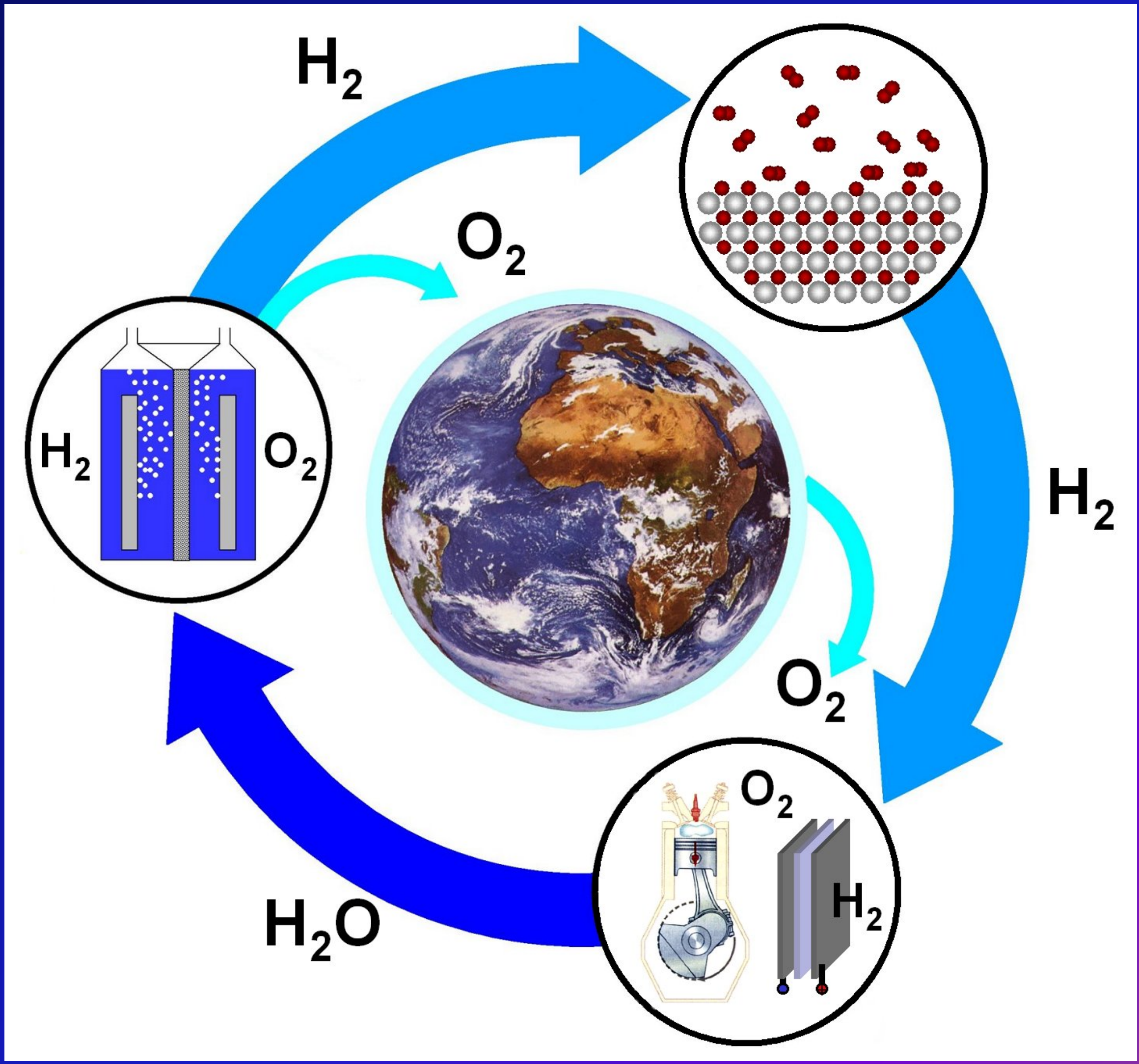
Energy carriers

- Energy carriers stores energy from the primary energy resource so it can be “carried” and used in the conversion device where and when needed.
  - Examples:
    - Electricity
      - Primary energy resource – nuclear, coal, petroleum, wind …
      - Transported and stored through the grid for use in ones home & …
      - End-use - a light bulb converts the electrical energy to light
    - Hydrogen
      - Primary energy resource – nuclear, coal, petroleum, wind …
      - Transported and stored for use in an automobile & …
      - End-use an engine or fuel cell to convert the stored chemical energy to kinetic energy – move the car down the road.
    - Any others?
      - I can’t think of any.

Hydrogen is an Energy Carrier – it is just like Electricity & its Conserved





Batteries vs Fuel Cells

- Fuel Cells and Batteries are both electro-chemical conversion devices that take stored chemical energy (between a fuel and an oxidizer) and convert it to electricity.
  - The battery has the fuel and oxidizer stored ***inside*** the electo-chemical device (the box).
    - The amount of energy a battery can store is limited by the size of the electro-chemical box.
  - The fuel cell has the fuel and oxidizer stored ***outside*** the electo-chemical device
    - The amount of energy a fuel cell can store is limited by the size of the "fuel tank".
      - The oxidizer is generally taken from the atmosphere.

Battery Electric Vehicles (BEV) vs Fuel Cell Electric Vehicles (FCEV)

- Both are electric vehicles -- the only difference is how the energy is stored on board
  - BEV - Batteries (scales linearly - the number of batteries –> n, the weight also scales like n)
  - FCEV - Hydrogen in a tank (scales volumetrically -> like r^3, the weight increase is insignificant)
- Take Note! Electric motors have huge torque at zero velocity! Electric vehicles accelerate fast from a stop.

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They are really fun to drive!

Estimated Refuel times for a 300 mile range Toyota Highlander (175kWHr)

- Gasoline – (Combined Highway & City eff. 17%)
  - ~ 5 minutes – 13.6 gal @~22 mpg
- Fuel Cell EV – (Combined Highway & City eff. ~50%)
  - ~ 8 minutes – 4.6 kg @70 MPa
- Grid EV – (Combined Highway & City eff. ~65%)
  - 43.7 min – Type III (480V, 500Amp, three phase)
  - 18.2 hr – Type II (240V, 40Amp, single phase)
  - 72.9 hr – Type I (120V, 20Amp, single phase)
  - 97.2 hr – Type I (120V, 15Amp, single phase)

OEM's have given up on full service BEVs for full size vehicles.

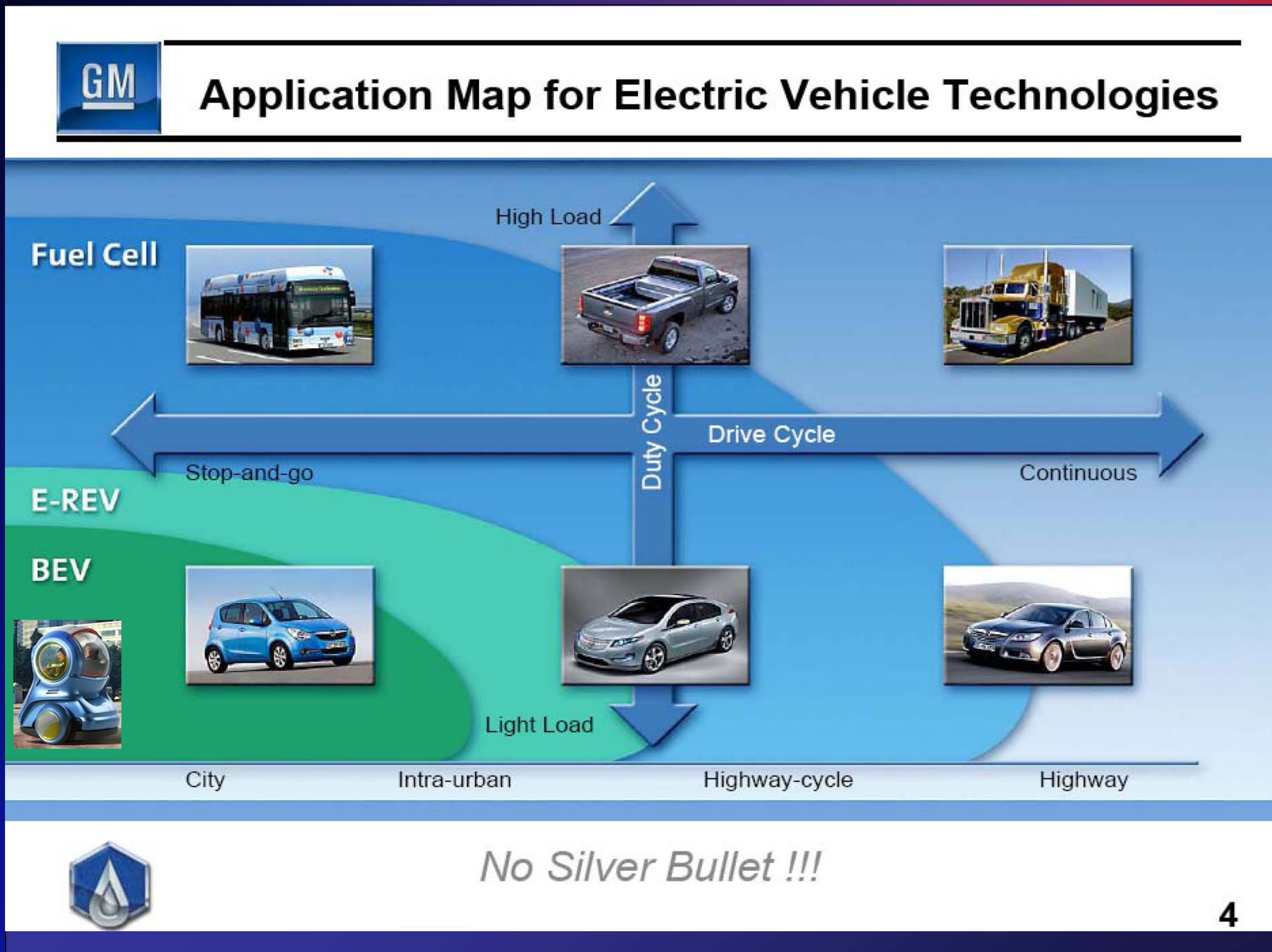
- "Even with complete success in meeting the USABC long-term goals for battery energy capacity, electric vehicles cannot compete with hydrogen-fueled vehicles for general usage in terms of range and 'refill' time. **Use of hydrogen as a transportation fuel as on-board storage for useful range and refill time is already available (if not optimal)"**
  - ...Quoted from "Hydrogen Research for Transportation: The USCAR Perspective; July 2009"

USABC – US Advanced Battery Consortium

BEV – Battery Electric Vehicles

USCAR – US Council for Automotive Research

OEM's are Electrifying the fleet



Nikola unveils its hydrogen-powered semi-truck

Toyota Project Portal fuel cell truck vs. diesel

https://www.youtube.com/watch?v=Z1yYueiCHzA

Norwegian future value chains
for liquid hydrogen

“The dawn of Low-Carbon Shipping”

- “Container ships and other maritime vessels currently run on pollutant-intensive heavy fuel oil. The world's largest container-shipping company, Maersk, has promised to make its operations zero carbon by 2050. Doing so will require using new fuels such as hydrogen.”
  - » NPR, Rebecca Hersher

“Shipping Industry Buckles to Carbon Pressure”

- “We now know the international shipping industry is responsible for 18% of some air pollutants. Moreover the International Maritime Organization blames giant ships for 2.2% of global emissions caused by humans. These could rise by as much as 250% if we do nothing. Therefore, we welcome it when the shipping industry buckles under pressure to take action.”
  - Battery Technical
    - Richard

Norled's Hydrogen Ferries

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January 21, 2020

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Evens, Greg; Sandia National Laboratories
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Houf, Bill; Sandia National Laboratories
Merilo, Eric; SRI International
Moen, Chris; Sandia National Laboratories
Schefer, Bob; Sandia National Laboratories
Tchouvelev, Andrei, Tchouvelev & Associates

Hydrogen Myths

- Hindenburg
  - Hydrogen Caused the Disaster
- Hydrogen Molecular Diffusivity is 3.8 times that of CH_4
  - Therefore it diffuses rapidly and mitigates any hazard
- Hydrogen is 14.4 times lighter than air
  - Therefore it rapidly moves upward and out of the way
- We do not know the flammability limits for H_2

Hydrogen Myths

- We just do not understand hydrogen combustion behavior
  - Hydrogen release is different than other fuels
  - Radiation is different than other fuels
- Hydrogen hazards can be compared favorably to experiences with other hydrocarbon fuels
  - Less dangerous than gasoline, methane …
- Hydrogen always ignites
  - Joule-Thomson heating, Static electric discharge, Shock heating …
- Hydrogen is toxic and will cause environmental harm
  - "… We need to be indemnified against a hazardous toxic hydrogen spill …" – Generic Insurance Company

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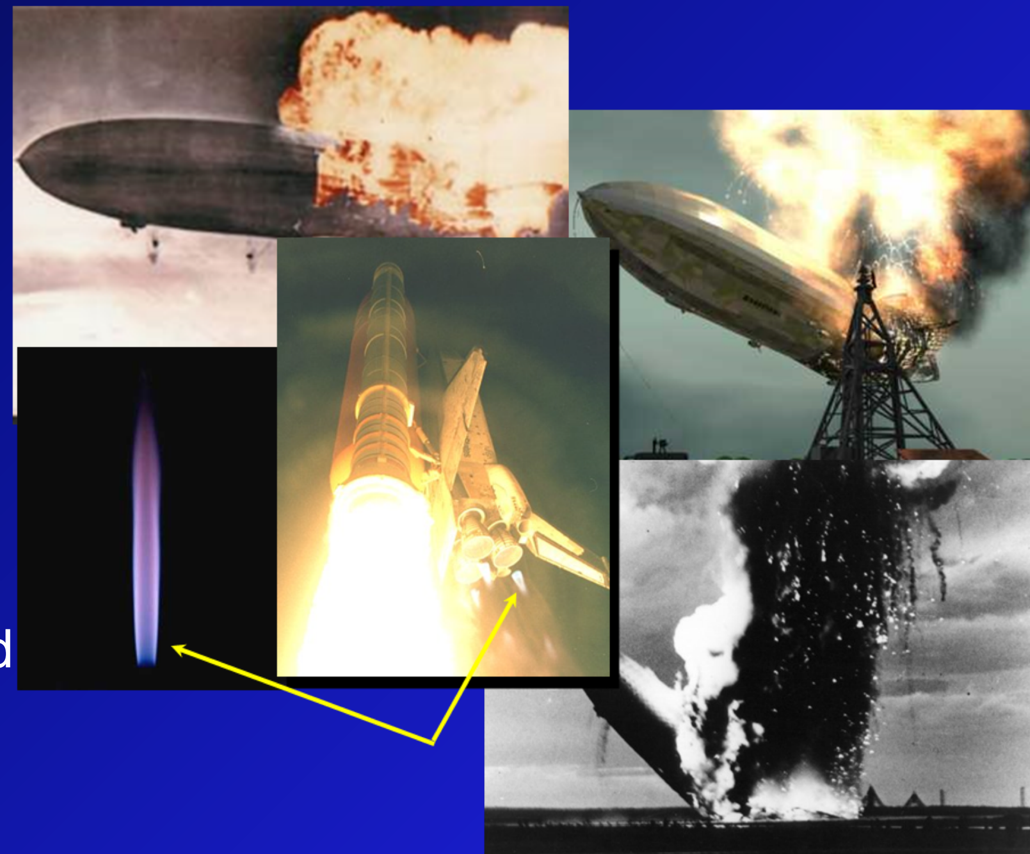
Let's get this out of the way! Hindenburg Disaster

- 36 out of 97 died mostly trapped by the fire of fabric, diesel fuel, chairs, tables … (not hydrogen)
- The craft did not explode but burned – and while burning stayed aloft (Hydrogen was still in the nose)
- The craft fell to the ground tail first – the nose was still full of hydrogen



- Radiation from the flame was red, orange and yellow – hydrogen flames emit in the near UV ~304 to 350 nm (OH* lines), 680 nm to 850 nm (vibrationally excited H_2O), and ~0.5 to 23 mm (water bands)

Lets get this out of the way! Hindenburg Disaster (Cont'd)

- The covering was coated with cellulose nitrate or cellulose acetate -- both flammable materials. Furthermore, the cellulose material was impregnated with aluminum flakes to reflect sunlight. -- Dr. Addison Bain

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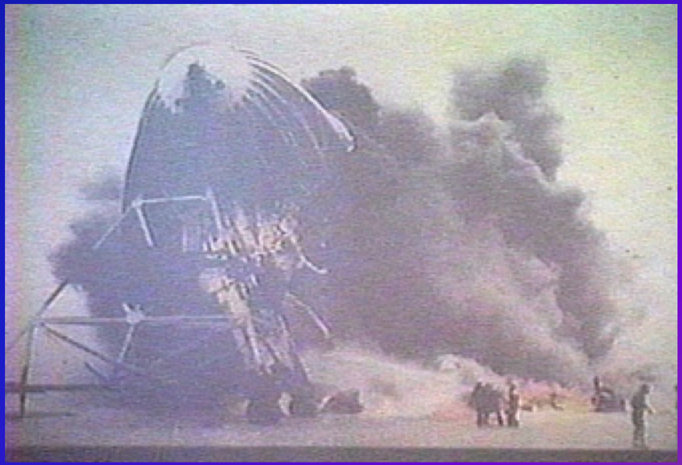

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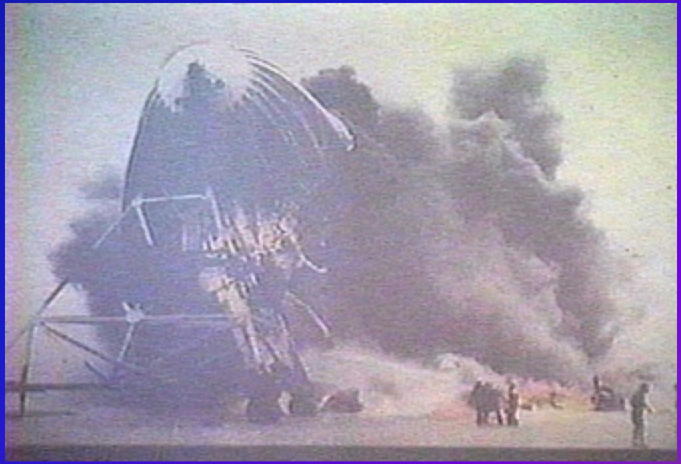

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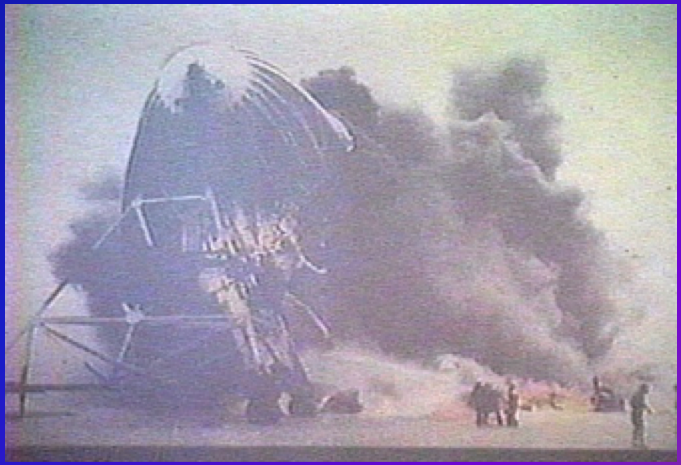
- "I guess the moral of the story is, don't paint your airship with rocket fuel."

  -- Dr. Addison Bain



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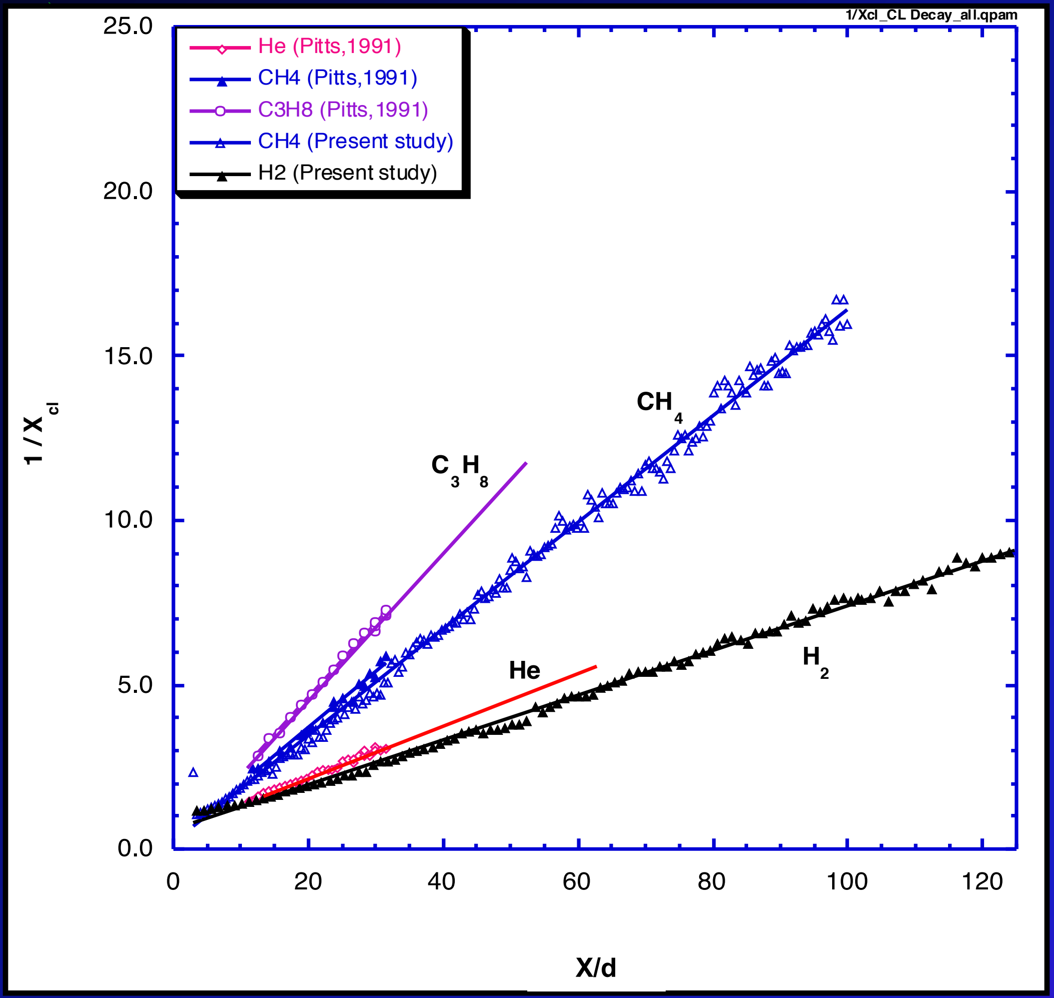
Small Unignited Releases: Momentum-Dominated Regime

Data for round turbulent jets



- In momentum-dominated regime, the centerline decay rate follows a 1/x dependence for all gases.
- The mole fraction centerline decay rate increases with increasing molecular weight.

The decay rate for H_2 is significantly slower than for methane and propane.

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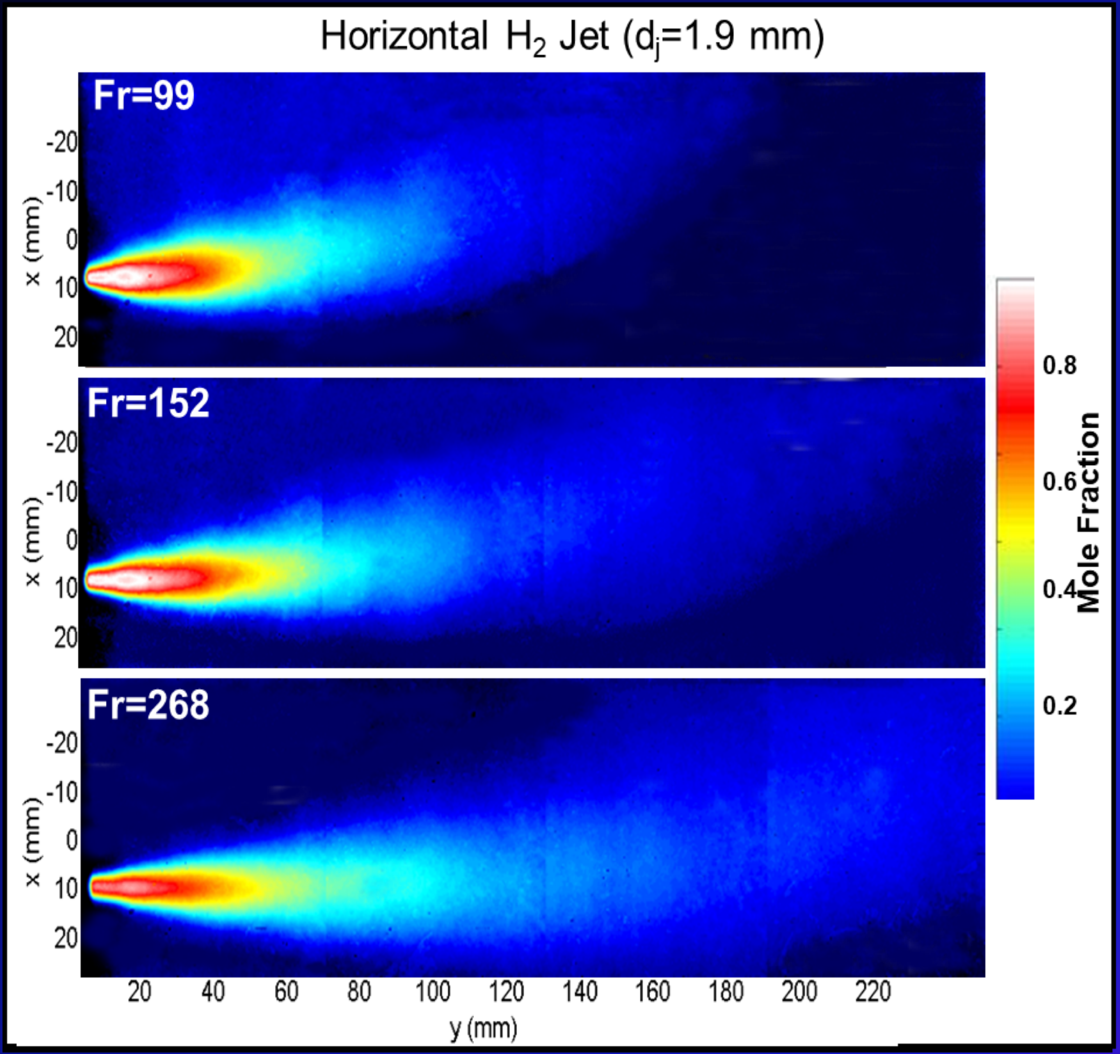
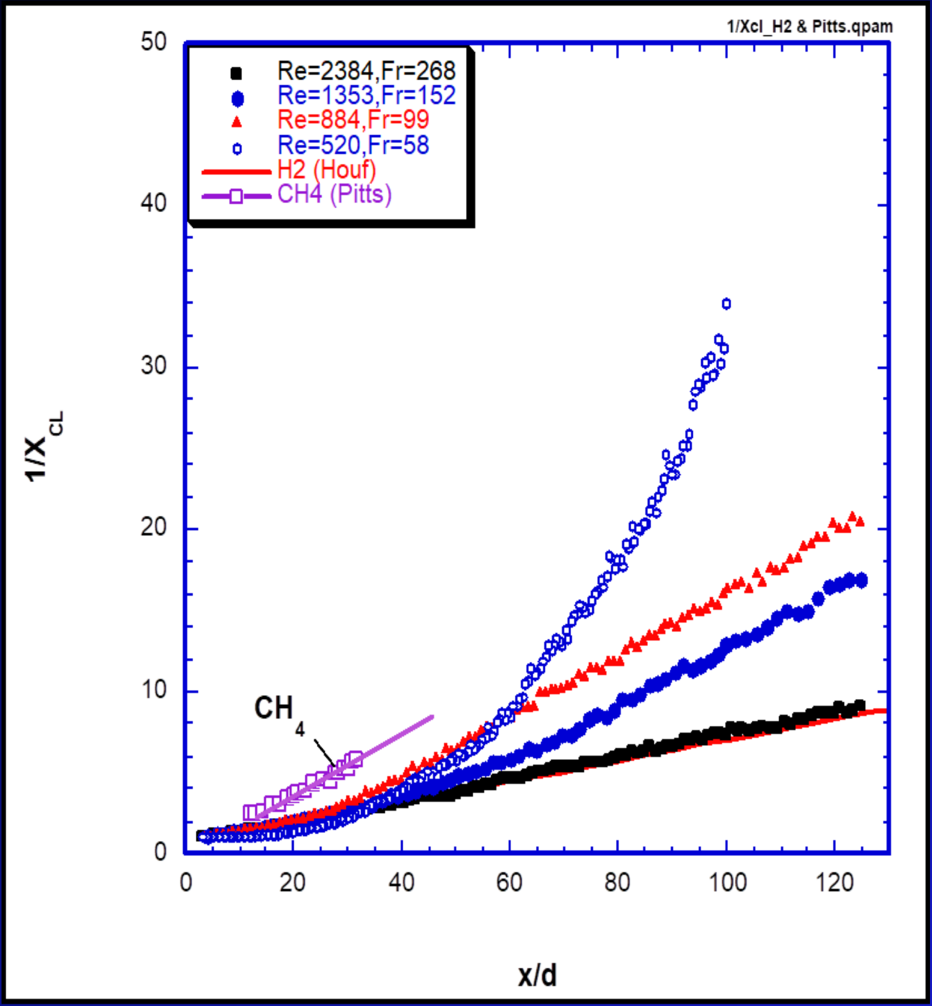
Buoyancy effects are characterized by Froude number



- Time-averaged H_2 mole fraction distributions.
- Froude number is a measure of strength of momentum force relative to the buoyant force
- Increased upward jet curvature is due to increased importance of buoyancy at lower Froude numbers.

Small Unignited Releases: Buoyancy Effects



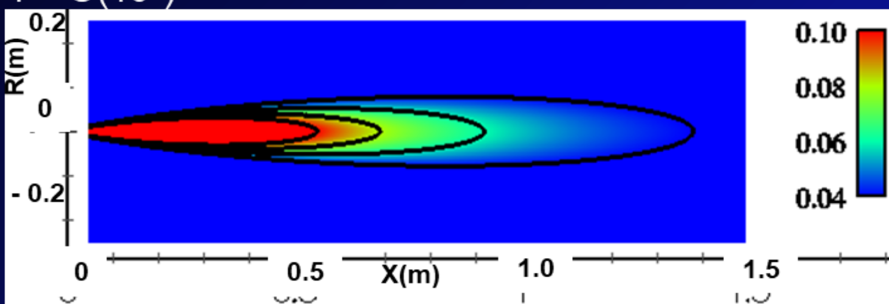
- Data for round H_2 Jets (d_j=1.91 mm)
- At the highest Fr, $1/X_{CL}$ increases linearly with axial distance, indicating momentum dominates.
- As Fr increases buoyancy forces become less important and the centerline decay rate decreases.
- The transition to buoyancy-dominated regime moves downstream with increasing Fr.

Choked & Unchoked Flows at 20 SCFM

Tank Pressure = 3000 psig, Hole Dia. = 0.297 mm

Exit Mach Number = 1.0 (Choked Flow)

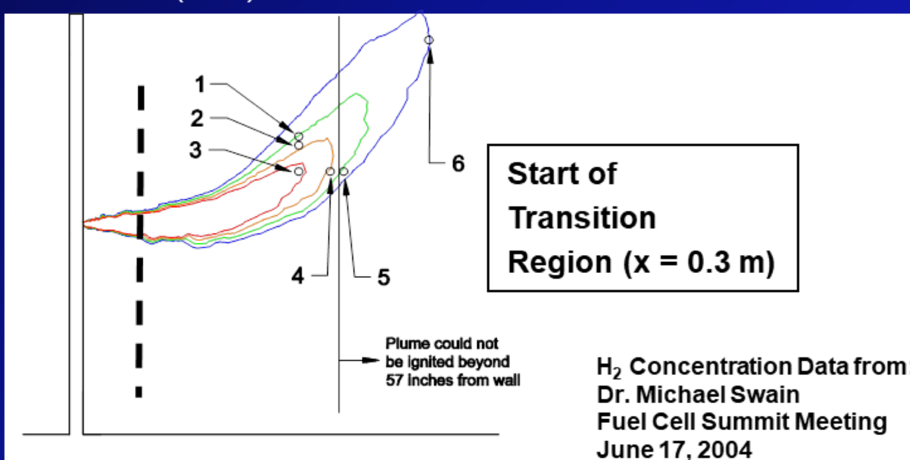
Fr ~ O(10^4)



Flowrate = 20 scfm, Hole Dia. = 9.44 mm

Exit Mach Number = 0.1 (Unchoked Flow)

Fr ~ O(100)



- Correlations based on experimental data
- Start Intermediate Region
  - $x/D = 0.5\ F^{1/2}(\rho_{exit}/\rho_{amb})^{1/4}$
- End Intermediate Region
  - $x/D = 5.0\ F^{1/2}(\rho_{exit}/\rho_{amb})^{1/4}$
- F = Exit Froude No.

  $= U^2_{exit}\ \rho_{exit}/(gD(\rho_{amb} - \rho_{exit}))$

Start Transition Region -> x = 6.3 m

- Assuming gases at 1 Atm, 294K (NTP)
  - Red – 10.4%
  - Orange – 8.5%
  - Green – 5.1%
  - Blue – 2.6%

Momentum-Dominated Jets are within the Ignition Region

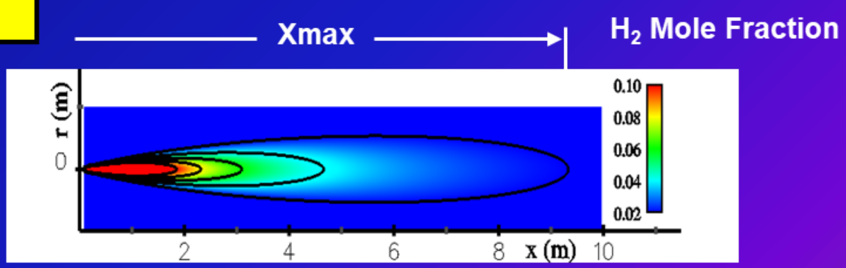
Unignited Jet Separation Distance Length Scales

Pressure = ~20 MPa (~3000 psig)

Hole Diameter	Flowrate	Xmax - Distance to 4% mole fraction	Start of Intermediate Region
3.175 mm (1/8 inch)	9.718×10^{-2} Kg/sec ($2{,}463$ ft^3/min)*	14.80 m (48.55 ft)	20.7 m (67.9 ft)
1.5875 mm (1/16 inch)	2.430×10^{-2} Kg/sec (615.9 ft^3/min)*	7.40 m (24.28 ft)	14.6 m (48.0 ft)
0.794 mm (1/32 inch)	6.075×10^{-3} Kg/sec (154.1 ft^3/min)*	3.70 m (12.14 ft)	10.3 m (33.9 ft)

*@NTP = 21° C (70° F), 101 kPa (14.7 psia)

Flow between exit and 4% mole fraction is in the momentum dominated regime



- **Start Intermediate Region**

  $x/D = 0.5\, F^{1/2} (\rho_{exit}/\rho_{amb})^{1/4}$

F = Exit Froude No. $= U^2_{exit}\, \rho_{exit} / (gD(\rho_{amb} - \rho_{exit}))$

Hydrogen Myths

- Hindenburg
  - Hydrogen Caused the Disaster
- Hydrogen Molecular Diffusivity is 3.8 times that of CH_4
  - Therefore it diffuses rapidly and mitigates any hazard
- Hydrogen is 14.4 times lighter than air
  - Therefore it rapidly moves upward and out of the way
- We do not know the flammability limits for H_2

Flammability Limits for H_2

Upward Flame Propagation

Tube Dimensions, cm		Firing end	Limits, percent		Water Vapor Content	Reference
Diameter	Length		Lower	Higher		
7.5	150	Closed	4.15	75.0	Half-saturated	356
5.3	150					
5.3	150					
5.3	150					
5.0	150					
5.0						
4.8						
4.5						
4.5						

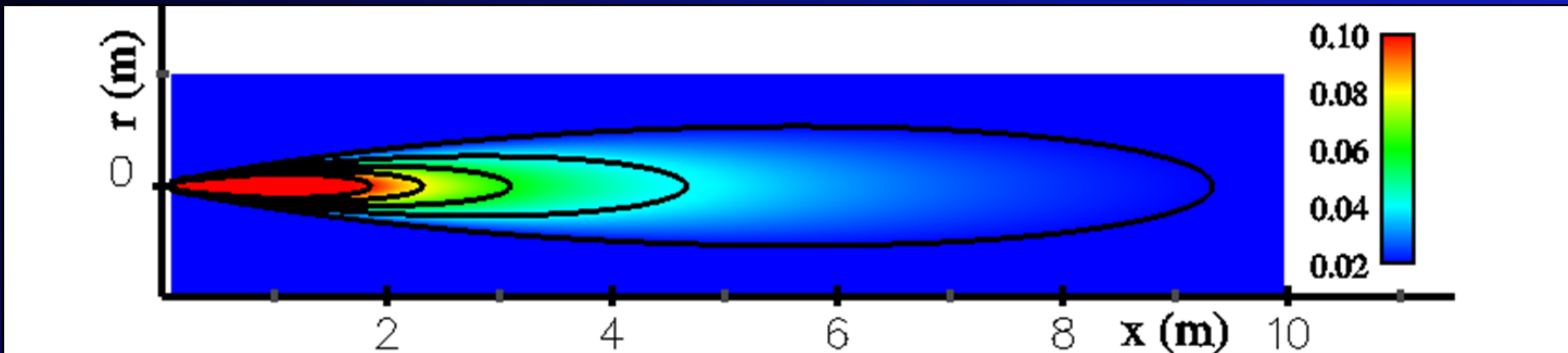
Horizontal Flame Propagation

Not stated	N	8.5	67.5	N	82
1,000	N	8.7	75.5	N	95
810	N	5.0	73.5	N	349
350	N	4.6	70.3	N	368
35	N	9.4	64.8	N	297

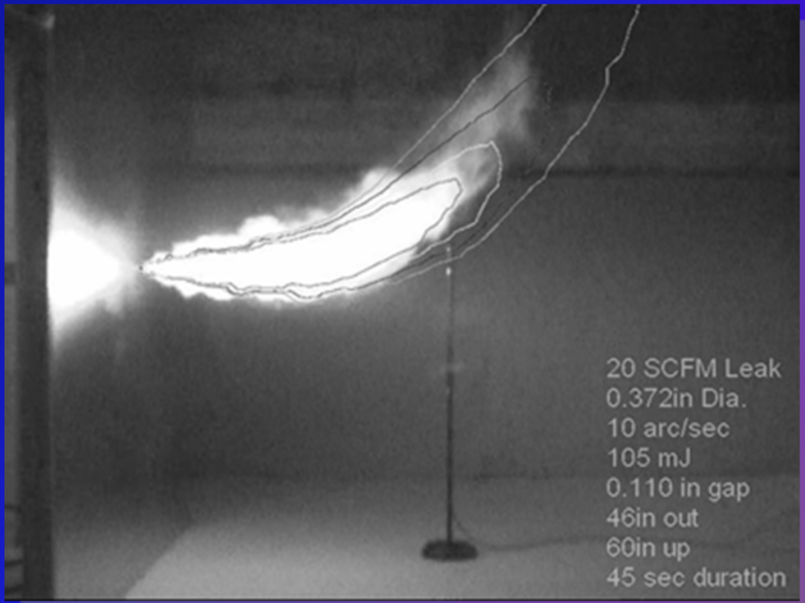
Tube Dim… cm		Firing end	
Diameter	Length		Lower
21.0	31	Open	9.3
8.0	37	Closed	8.9
7.5	150	N	8.8
7.0	150	N	-----
6.2	33	Open	8.5
6.0	120	N	9.45

- ***78 investigations of hydrogen flammability limits were identified between 1920 and 1950.***
- ***Hydrogen flammability limits are well established.***

What is a Reasonable Flame Stabilization Limit?



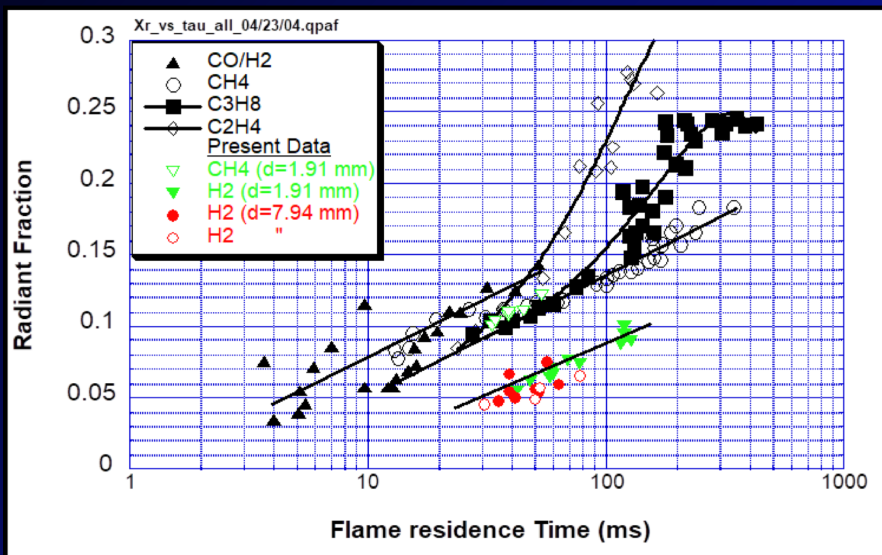
- Which volume fraction contour is relevant:
  - lean flammability limit? … 4% or 8%
  - detonation limit? … 18%
  - a fraction of the lowest lean flammability limit? … 1%
- ***Ignition of hydrogen in turbulent jets occurs around 8% as measured by Swain.***
  - This is consistent with the downward propagating limit of 8%

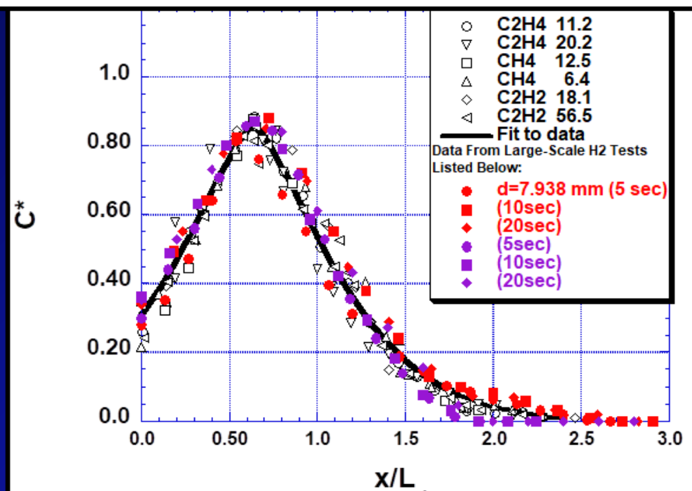


Hydrogen Myths

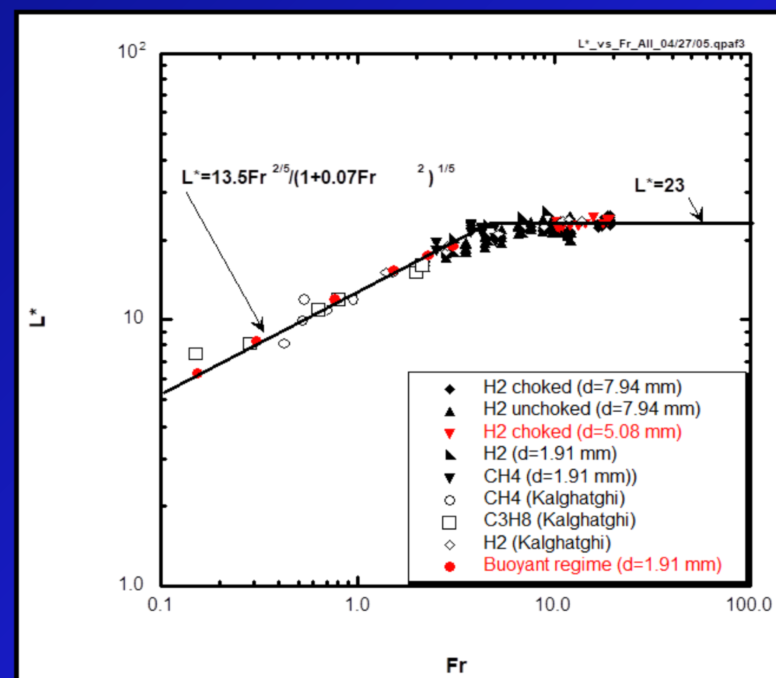
- We just do not understand hydrogen combustion behavior
  - Hydrogen release is different than other fuels
  - Radiation is different than other fuels
- Hydrogen hazards can be compared favorably to experiences with other hydrocarbon fuels
  - Less dangerous than gasoline, methane …
- Hydrogen always ignites
  - Joule-Thomson heating, Static electric discharge, Shock heating …
- Hydrogen is toxic and will cause environmental harm
  - "… We need to be indemnified against a hazardous toxic hydrogen spill …" – Generic Insurance Company

Hydrogen jets and flames are similar to other flammable gases

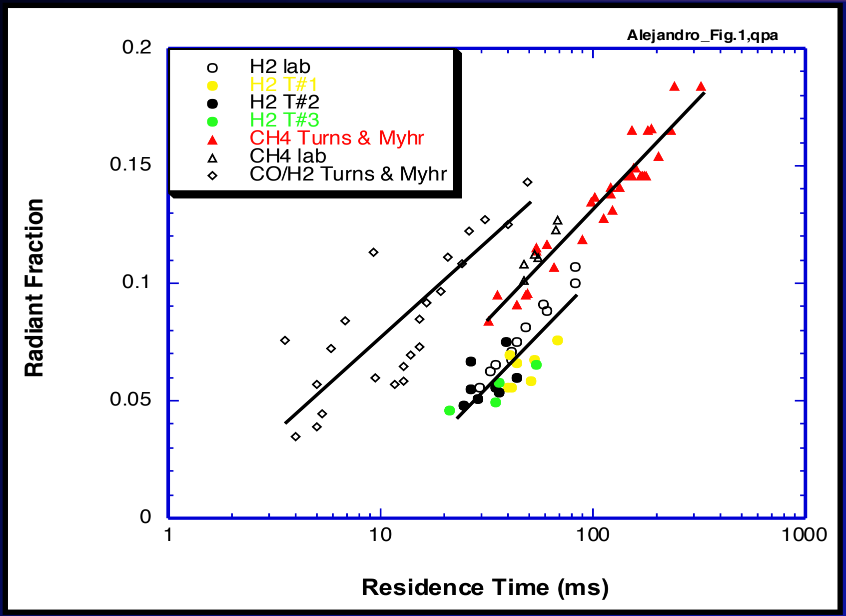




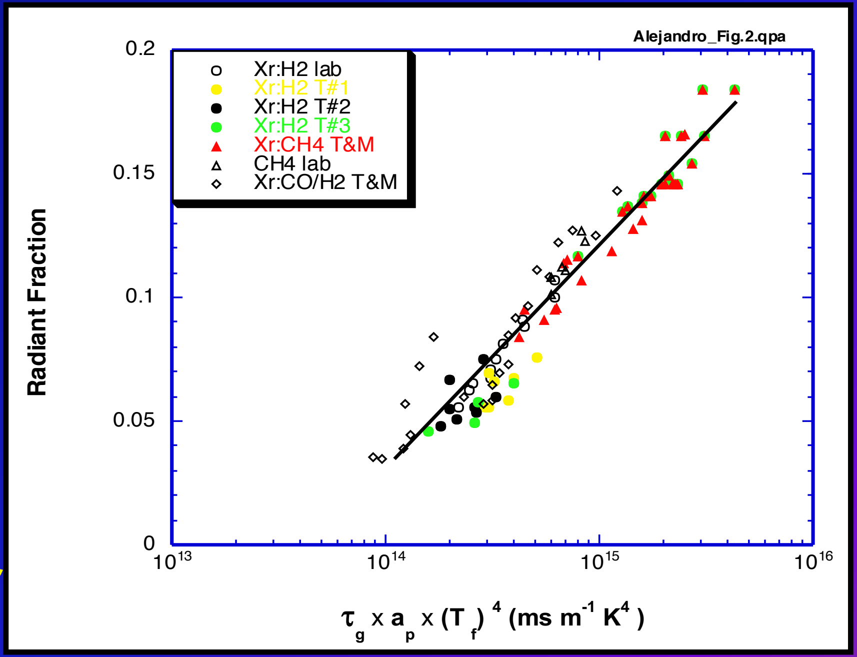
- Fraction of chemical energy converted to thermal radiation
- Radiation heat flux distribution
- Jet length



Thermal Radiation from Hydrogen Flames



- Previous radiation data for *nonsooting* CO/H_2 and CH_4 flames correlate well with flame residence time.
- Sandia's H_2 flame data is a factor of two lower than the hydrocarbon flame data.



- Radiation heat flux data collapses on singe line when plotted against product $\tau_G \times a_p \times T_f^4$.
- a_p (absorption coefficient) is factor with most significant impact on data normalization

⇨ ***Plank mean absorption coefficient for different gases must be considered***

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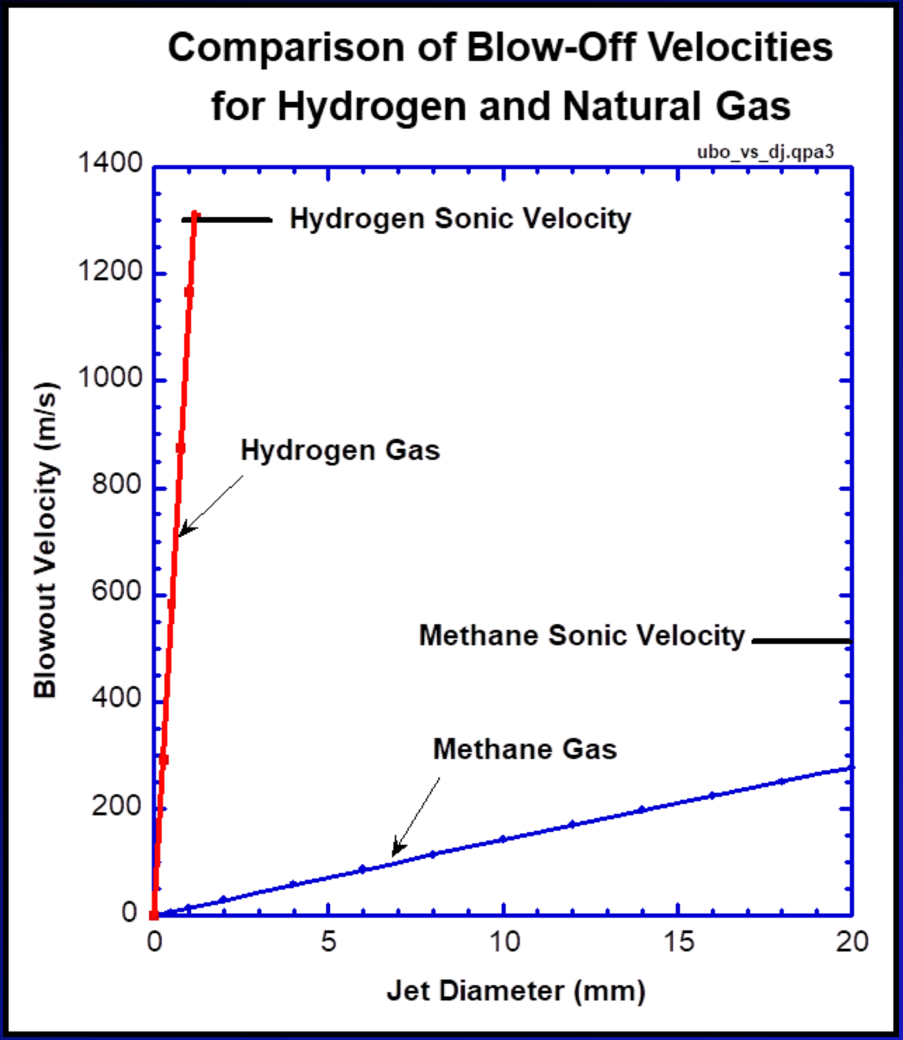
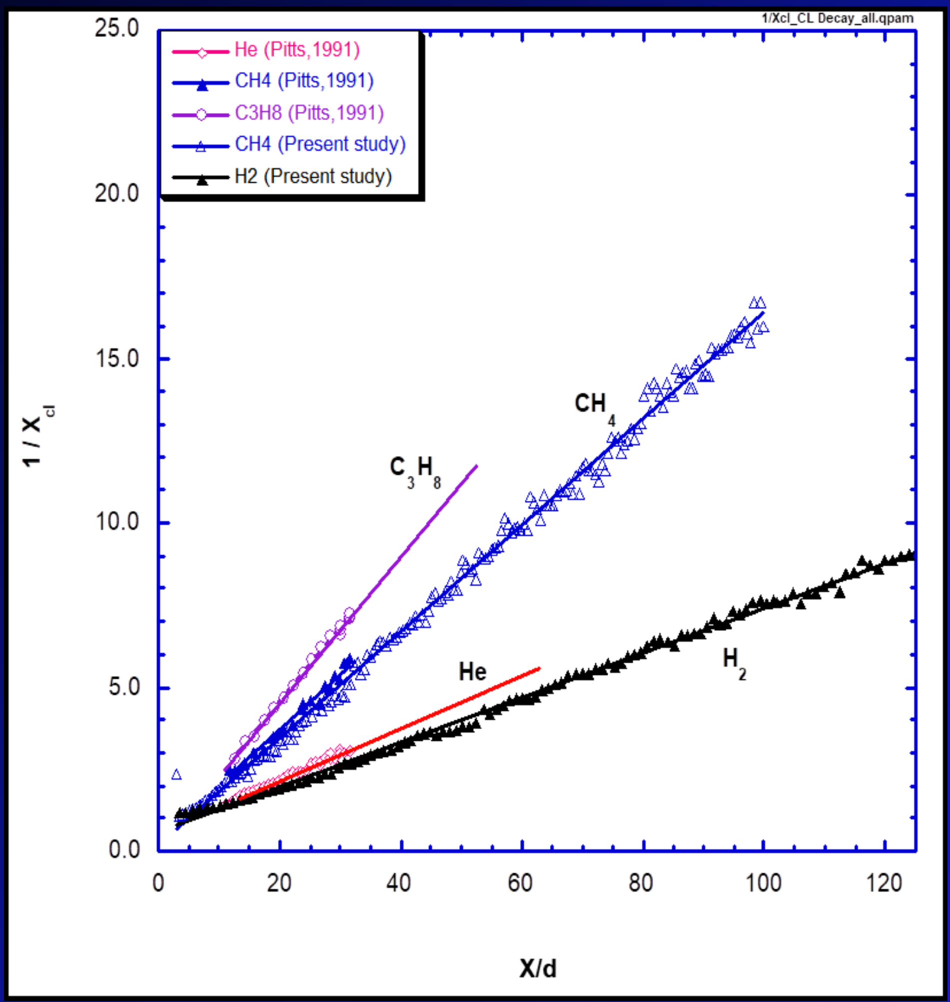
Comparisons of NG and H_2 Behaviors



- Assume 3.175 mm (1/8 inch) dia. hole
- Unignited jet lower flammability limits
  - LFL H_2 - 4% mole fraction
  - LFL NG - 5% mole fraction
- Flame blow-off velocities for H_2 are much greater than NG
- Flow through 1/8" diameter hole is choked
  - V_{sonic} = 450 m/sec for NG (300K)
  - V_{sonic} = 1320 m/sec for H_2 (300K)
- Hole exit (sonic) velocity for NG is greater than NG blow-off velocity
  - No NG jet flame for 1/8" hole
- Hole exit (sonic) velocity for H_2 is much less than blow-off velocity for H_2
  - H_2 jet flame present for 1/8" hole

Small Unignited Releases: Momentum-Dominated Regime

Data for round turbulent jets



- In momentum-dominated regime, the centerline decay rate follows a 1/x dependence for all gases.
- The mole fraction centerline decay rate increases with increasing molecular weight.

The decay rate for H_2 is significantly slower than for methane and propane.

Unignited jet concentration decay distances for NG and H_2.

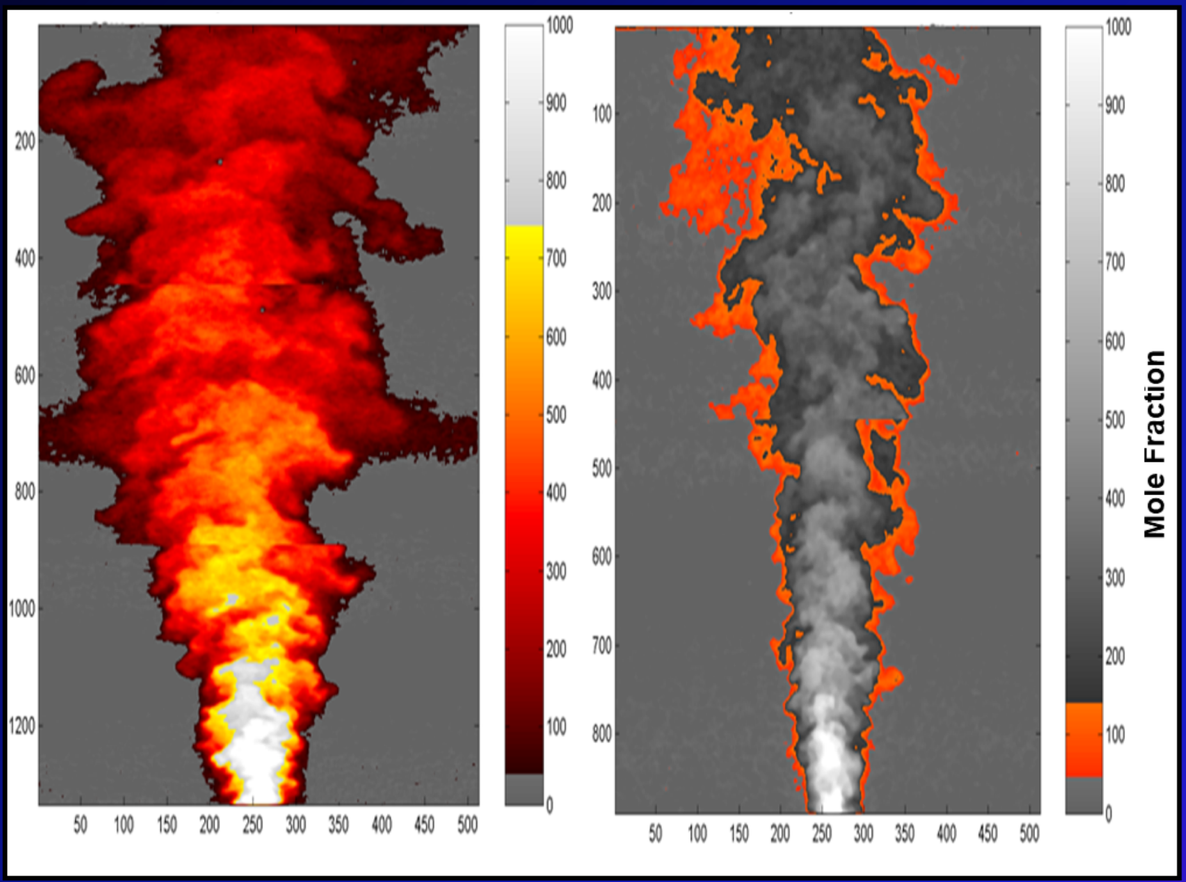
Distance on Jet Centerline to Lower Flammability Limit for Natural Gas and Hydrogen

Tank Pressure	Hole Diameter	Distance to 5% Mole Fraction Natural Gas	Distance to 4% Mole Fraction. Hydrogen
18.25 bar (250 psig)	3.175 mm (1/8 inch)	1.19 m (3.90 ft)	4.24 m (13.91 ft)
	1.587 mm (1/16 inch)	0.59 m (1.93 ft)	2.12 m (6.95 ft)
207.8 bar (3000 psig)	3.175 mm (1/8 inch)	3.92 m (12.86 ft)	13.54 m (44.42 ft)
	1.587 mm (1/16 inch)	1.96 m (6.43 ft)	6.77 m (22.21 ft)

Distance to the lower flammability limit for hydrogen is about 3 times longer than for natural gas

Small Unignited Releases: Ignitable Gas Envelope

H_2 Jet at Re=2,384; Fr = 268 CH_4 Jet at Re=6,813; Fr = 478



- H_2 flammability limits: LFL 4.0%; RFR 75%
- CH_4 flammability limits: LFL 5.2%; RFR 15%

Radial profiles in H_2 jet, d = 1.91 mm, Re = 2384

Is there a myth about the minimum ignition energy?

- Lower ignition energy of H_2 is the lowest of the flammable gases at stoichiometry
  - Over the flammable range of CH_4 (~below 10%), however, H_2 has a comparable ignition energy.

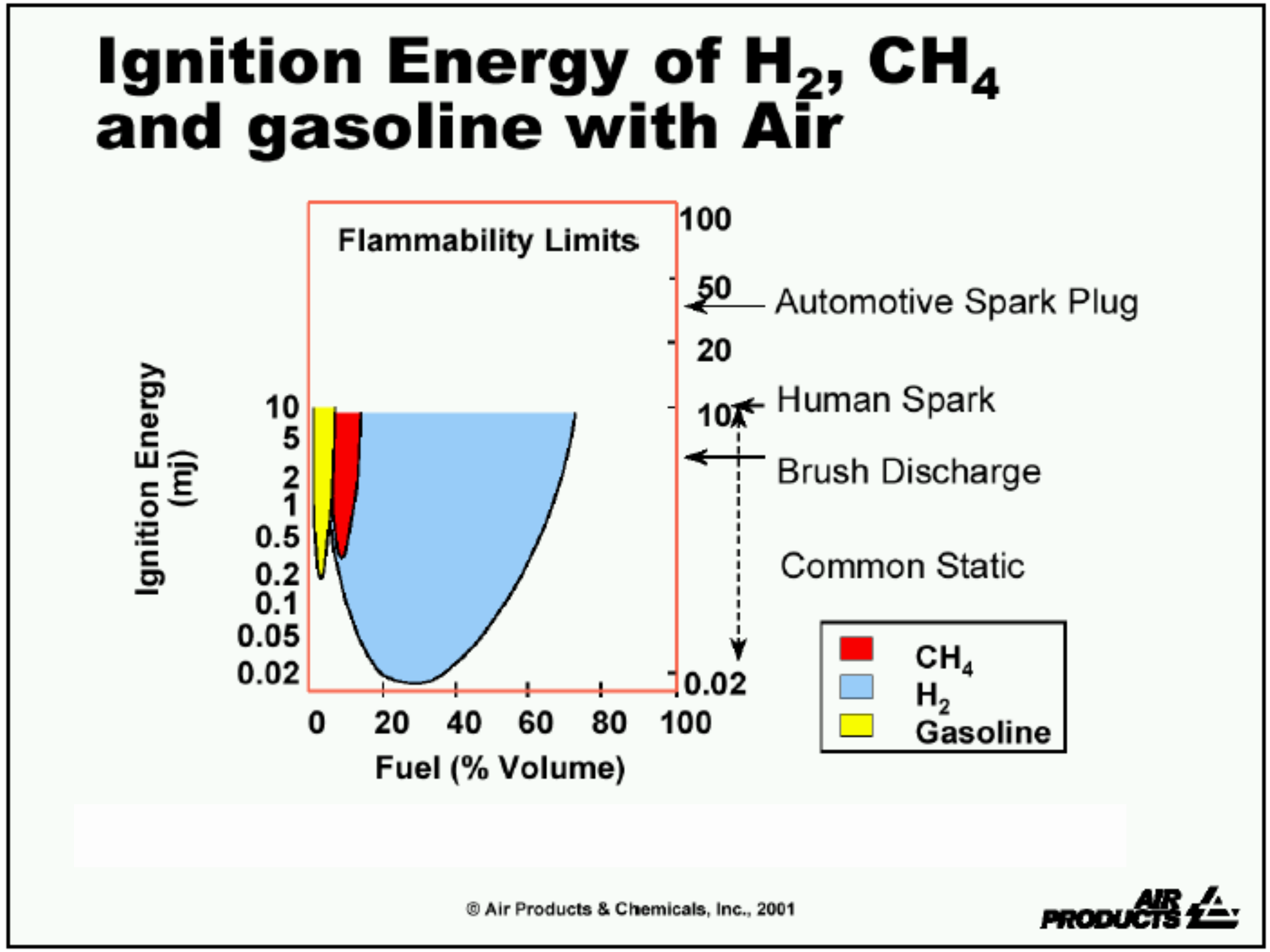


Figure 1: Flammability Limits vs. Ignition Energy of H_2, CH_4 and Gasoline in Air

Hydrogen Myths

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Spontaneous Ignition?

Proposed Mechanisms for Spontaneous Ignition

- 81 ignitions of H_2 releases have been reported (MHIDAS database). In 11 cases the ignition source was identified (flame, electric, hot surface). *In the remaining 70 no ignition source could be identified*.
- Proposed causes include the following:
  - Joule-Thomson
  - Static charge buildup in the flow
  - Shock heating that leads to ignition of H_2/air mixtures
  - Catalytic reaction with materials present in the flow (iron oxide)
  - Friction heating of particulates / hot surface ignition

Proposed Mechanisms for Spontaneous Ignition -- ???

- We are still working on this one – so far there is no definitive explanation?

Hydrogen Myths

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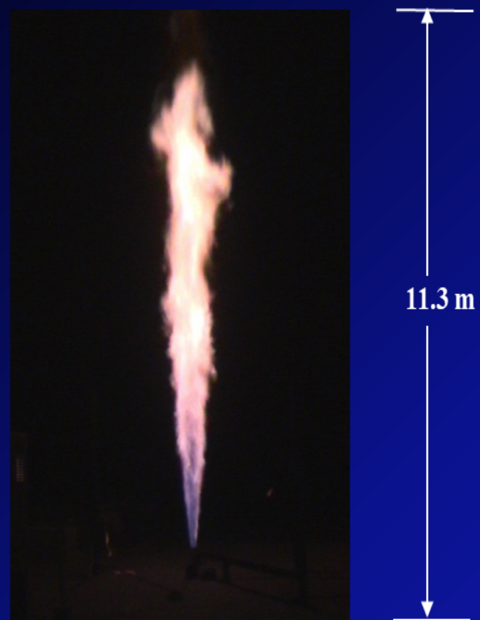
Some people just do not get it!

- ⇨ H_2
  - ➢ is not toxic,
  - ➢ it is environmentally benign
  - ➢ We just borrow it -- ($2H_20 + E \text{ -> } 2H_2 + O_2$; then $2H_2+O_2 \text{ -> } 2H_2O + E$)
- ⇨ H_2 is a fuel and as such has stored chemical energy
  - ➢ It has hazards associated with it
    - It is no more dangerous than the other fuels that store chemical energy
    - IT IS JUST different; *-- WE UNDERSTAND THE SCIENCE*

We will learn how to safely handle H_2 in the commercial setting just as we have for our hydrocarbon fuels.

Presentation End

Publication list



Nighttime photograph of ~40 MPa large-scale H2 jet-flame test (d_j = 5.08mm, L_{vis} = 10.6 m) from Sandia/SRI tests.

(1) Houf and Schefer, "Predicting Radiative Heat Fluxes and Flammability Envelopes from Unintended Releases of Hydrogen," accepted for publication Int. Jour. of Hydrogen Energy, Feb. 2006.

(2) Schefer, Houf, San Marchi, Chernicoff, and Englom, "Characterization of Leaks from Compressed Hydrogen Dispensing Systems and Related Components," Int. Jour. of Hydrogen Energy, Vol. 31, Aug. 2006.

(3) Molina, Schefer, and Houf, "Radiative Fraction and Optical Thickness in Large-Scale Hydrogen Jet Flames," Proceedings of the Combustion Institute, April, 2006.

(4) Houf and Schefer, "Rad. Heat Flux & Flam. Env. Pred. from Unintended Rel. of H2," Proc. 13th Int. Heat Tran. Conf., Aug., 2006.

(5) Schefer, Houf, Williams, Bourne, and Colton, "Characterization of High-Pressure, Under-Expanded Hydrogen-Jet Flames," submitted to Int. Jour. of Hydrogen Energy, 2006.

(6) Houf and Schefer, "Predicting Radiative Heat Fluxes and Flammability Envelopes from Unintended Releases of Hydrogen," 16th NHA Meeting, Washington, DC, March 2005.

(6) Schefer, R. W., Houf, W. G., Bourne, B. and Colton, J., "Turbulent Hydrogen-Jet Flame Characterization", Int. Jour. of Hydrogen Energy, 2005.

(7) Schefer, R. W., Houf, W. G., Bourne, B. and Colton, J., "Experimental Measurements to Characterize the Thermal and Radiation Properties of an Open-flame Hydrogen Plume", 15th NHA Meeting, April 26-30, 2004, Los Angeles, CA.

(8)Schefer R. W., "Combustion Basics," in National Fire Protection Association (NFPA) Guide to Gas Safety, 2004.

(9)P. Bénard (2007), Chapter 3 – Hydrogen Release and Dispersion - Release of hydrogen - section a.1, , Biennial Report on Hydrogen Safety, HySafe.

(10)B. Angers, A. Hourri, P. Bénard, P. Tessier and J. Perrin (2005), "Simulations of Hydrogen Releases from a Storage Tank: Dispersion and Consequences of Ignition". International Conference on Safety 2005, Sept 8-10, 2005, Pisa, Italy.

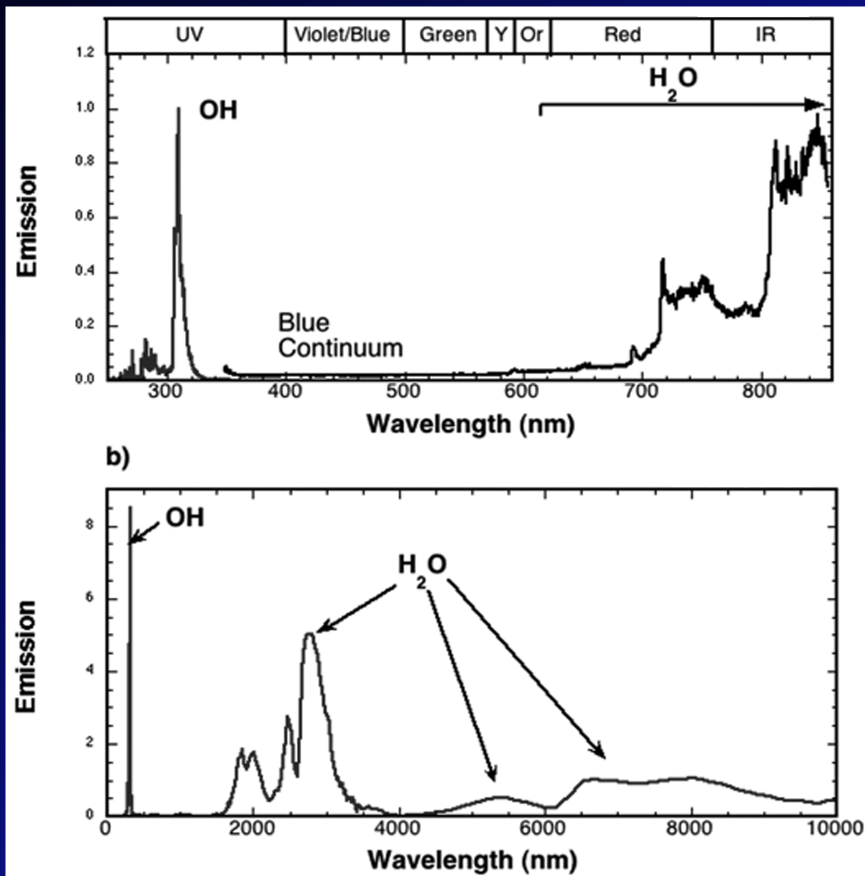
(11)A.V. Tchouvelev, P. Bénard, V. Agranat and Z. Cheng (2005), "Determination of Clearance Distances for Venting of Hydrogen Storage". International Conference on Safety 2005, Sept 8-10, 2005, Pisa, Italy (NRCAN, AUTO 21).

(12)Tchouvelev A., P. Bénard, D. R. Hay, V. Mustafa, A. Hourri, Z. Cheng, Matthew P. Large, Quantitative Risk Comparison of Hydrogen and CNG Refuelling Options, Final Technical Report to Natural Resources Canada for the Codes and Standards Workshop of the CTFCA, August 2006 (194 pages).

(13)Bénard, P., Tchouvelev, A., Hourri, A., Chen, Z., Angers, B. High Pressure Hydrogen Jets in a Presence of a Surface. Proceedings of International Conference on Hydrogen Safety, San Sebastian, Spain, September 2007.

(14)Tchouvelev, A.V., Howard, G.W. and Agranat, V.M. Comparison of Standards Requirements with CFD Simulations for Determining of Sizes of Hazardous Locations in Hydrogen Energy Station. Proceedings of the 15th World Hydrogen Energy Conference, Yokohama, June 2004.

H_2 Flame Radiation

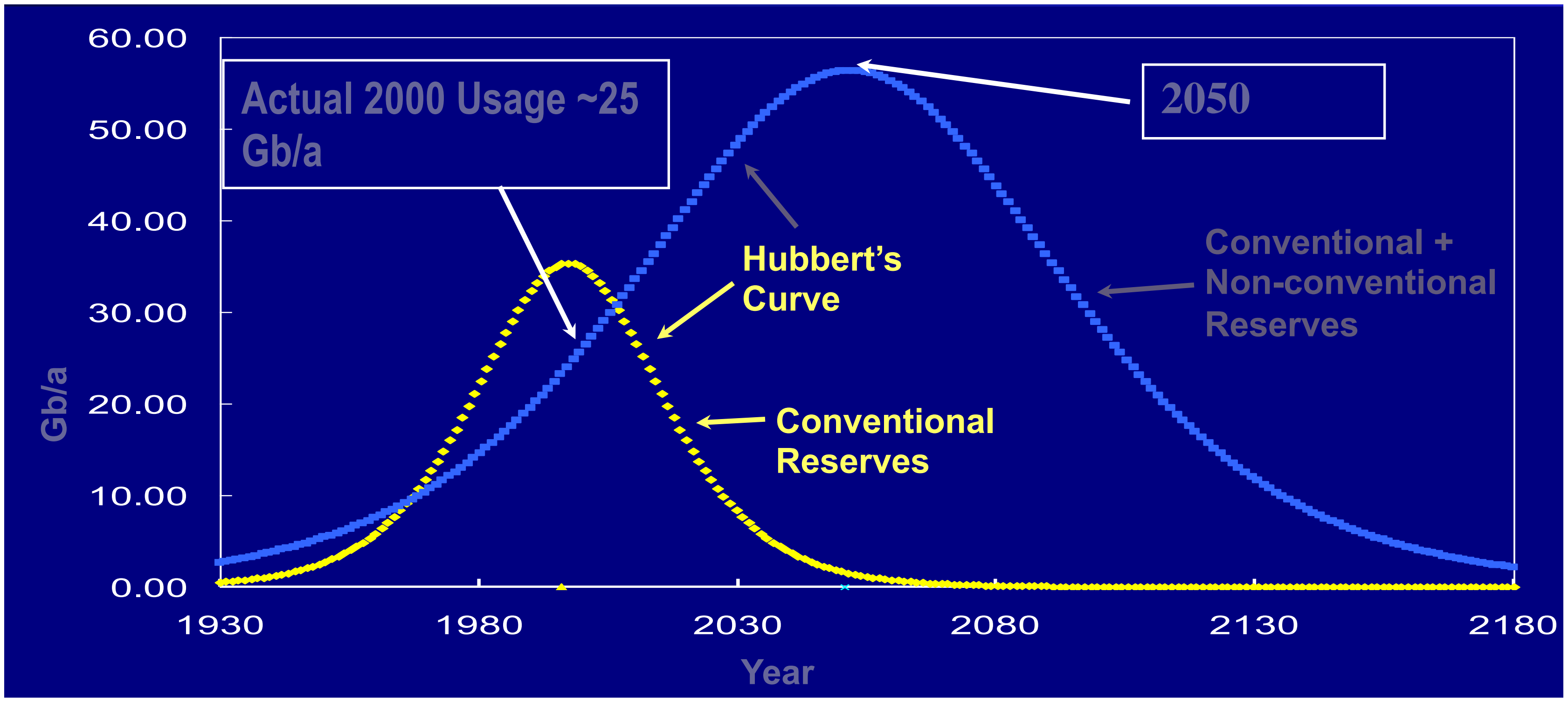


H_2O emission in IR accounts for 99.6% of flame radiation

- Orange emission due to excited H_2O vapor
- Blue continuum due to emission from OH + H => H_2O + hν
- UV emission due to OH*
- IR emission due to H_2O vibration-rotation bands

Oil Discovery

- Conventional Reserves
  - 1700 – 1800 Gb; used ~1000 Gb
- Predictions for the peak range from 2006 (Bakhitari) to 2025 (Shell) with no doubt it will happen *
- Oil Shale
  - ~3500 Gb
- Demand increasing ~3.0% / yr



OEM's are Electrifying the fleet

DAIMLER

Drivetrains for Various Driving Cycles

Long Distance

Suburban

Urban

Combustion Engine

Hybridization

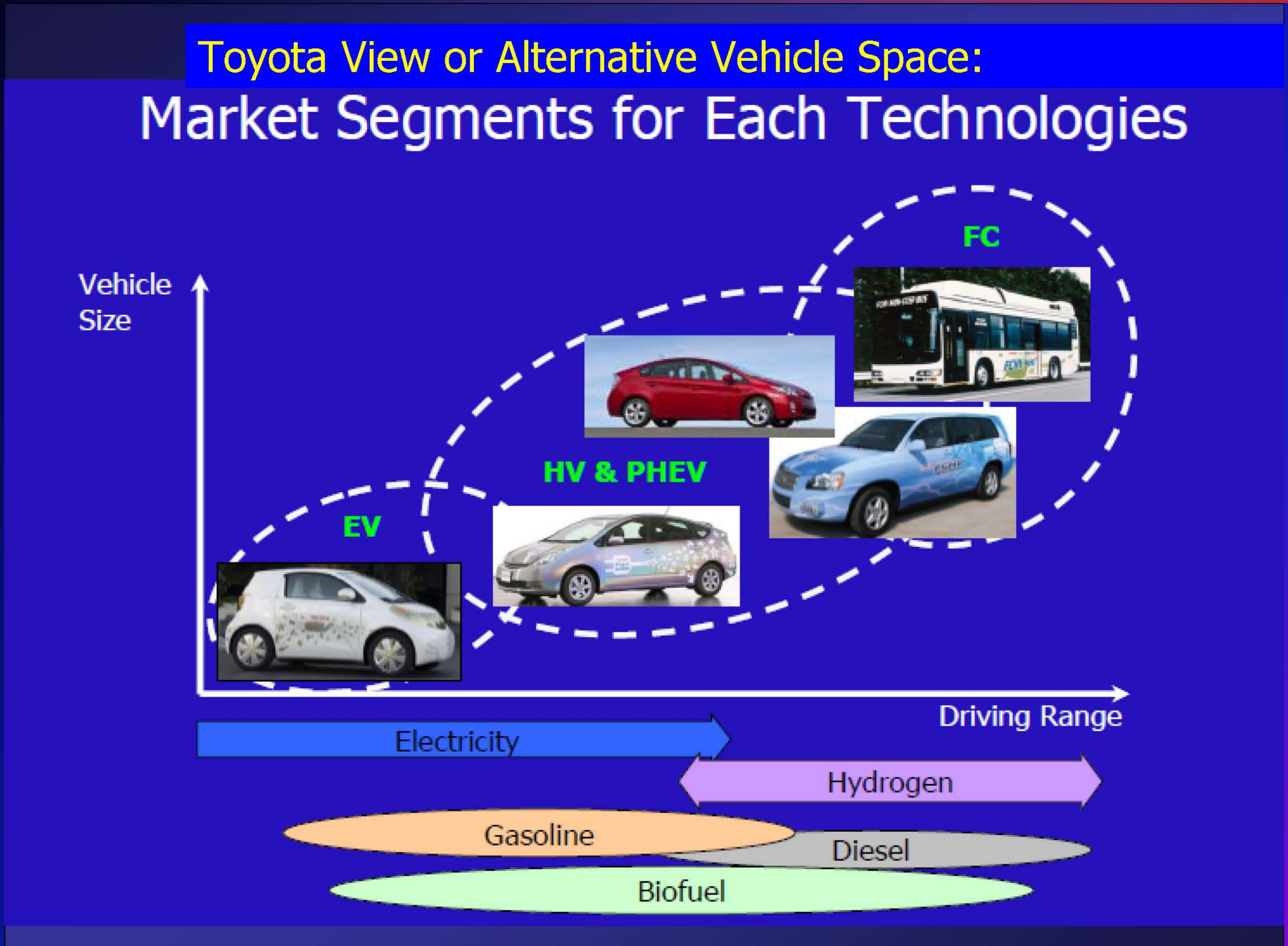
Plug-In/Range Extender

Electric Drive with Battery

Electric Drive with Fuel Cell

➢ **Only fuel cell technology is suited equally for both, short and long distance mobility**

OEM's are Electrifying the fleet



CHBC H_2 and Fuel Cell on-road workshop.